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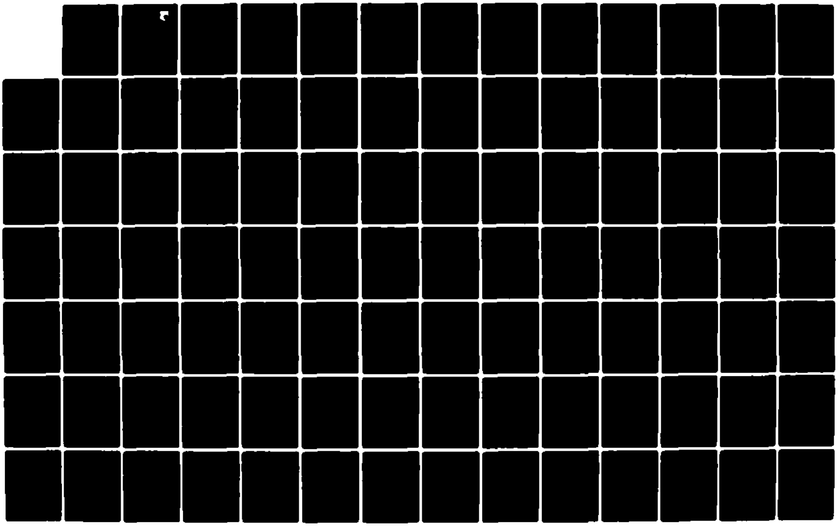

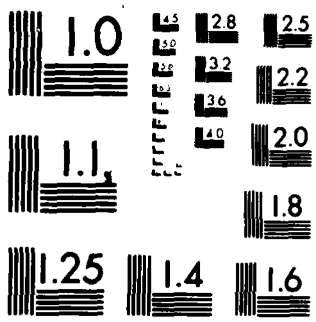

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VOLUME II

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USAF ADVANCED TERRESTRIAL ENERGY STUDY

VOLUME II: TECHNOLOGY HANDBOOK

Institute of Gas Technology
3424 S. State Street
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APRIL 1983

FINAL REPORT SEPTEMBER 1980-SEPTEMBER 1982

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of the USAF Advanced Terrestrial Energy Study. The objective of that study was to develop a data base of key parameters of selected energy conversion and energy storage technologies. The data base includes present and expected (through 2000) performance goals of the systems. The data base was established through an extensive literature search, surveys of manufacturers and researchers, and statistical and qualitative analyses of the available input data. The results of the study are reported in four documents:

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INTRODUCTION

A variety of energy systems undergoing research and development may provide the Air Force such benefits as reduced costs, greater reliability, and greater flexibility than conventional commercially available energy systems. This effort was funded to develop a data base of the key parameters of selected systems to serve as input to a multiple-criteria decision computer model that identifies the most appropriate energy technology for different Air Force needs. These data will also serve as an informational base for the Air Force's Civil Engineering and R&D communities.

The specific objective of this project was to describe a selected set of energy systems by a particular set of technical and economic parameters over the 1980-2000 time frame. To meet this objective, estimates of the performance parameters were developed for the years 1980, 1985, 1990, and 2000 at the following full-load power output ratings: 1.5, 5.0, 20.0, 30.0, 60.0, 100.0, 250.0, 500.0, 750.0, 1000, and 5000.0 kW.

This volume presents estimated parameter values for each of the technologies in the 1990 time frame to indicate the performance of each technology relative to other similar technologies. For each of the energy conversion technologies, the estimated parameter values are based on continuous duty (that is, operating 7884 hours per year) at design conditions with design performance for new equipment. Obviously, actual operating conditions will vary considerably depending on the application, the location, the age of the equipment, and other factors. The data developed in this study do not account for variances between actual operating conditions and design conditions.

Obviously, any broad data base has limitations, and this one is no exception. Primarily, the limitations result from the fact that the data represent a wide range of conditions and applications and as such could result in error if the data are taken at value for any unique, specific application. Recognizing this limitation, the expected errors of the predicted data were calculated and are included in Volume IV of this report. The expected errors represent the range of parameter values that can be expected at each output level, and to a great extent the ranges are the result of the need for a broad-based data base rather than a need for specific information for a single, unique application. Consequently, this data base should provide the

capability to screen technologies on a preliminary basis to identify the most appropriate technologies for selected applications relative to the other technologies.

The following energy conversion technologies are characterized in this data base:

- Gas turbines
  - Open cycle, nonrecuperative (nonregenerative)
  - Close cycle
  - Open cycle, recuperative (regenerative)
- Diesels
  - Turbocompounded
  - Turbocharged
  - Adiabatic
- Stirlings
  - Free piston
  - Kinematic
- Organic Rankine Cycles
- Fuel Cells
  - Phosphoric acid
  - Solid Polymer Electrolyte (SPE)
  - Molten carbonate
- Photovoltaics
  - Flat plate
  - Actively cooled
  - Photochemical
- Wind Turbines
  - Vertical axis
  - Horizontal axis.

The following energy storage technologies are characterized in this data base:

- Batteries
  - Zn/Cl_2
  - Zn/Br_2
  - Ni/Fe
  - $Li-Al/FeS_2$
  - Na/S
  - Advanced sealed lead-acids
  - Redox Cr-Fe
- Thermal Energy Storage Devices
  - $CaCl_2 \cdot 6H_2O$, calcium chloride hexahydrate
  - $Na_2SO_4 \cdot 10\ H_2O$, sodium sulfate decahydrate (Glauber's salt)
  - $Na_2S_2O_3 \cdot 5\ H_2O$, sodium thiosulfate pentahydrate
  - Olivine ceramic brick
  - Magnesite ceramic brick
  - Form-stable polyethylene

PARAMETER DEFINITIONS AND GENERAL ASSUMPTIONS

The data contained herein are to be used for a preliminary screening of technologies for certain applications. The user must recognize that the estimated parameter values were developed based on "average" or "generic" systems. For some technologies, such as wind turbine systems and photovoltaic systems, the site location will affect certain parameter values.

General Requirements

To minimize the ambiguity of estimated parameter values included in the data base, definitions and assumptions were adopted regarding the general requirements and/or applications of each energy technology.

For energy conversion technologies (that is, all of the technologies except batteries and thermal energy storage devices), each system is defined to include the technology and necessary balance-of-plant components (B.O.P.) to produce utility-quality power on a continous stand-alone basis (operating 90% of each year at the required power output level) from a designated primary energy source. Certain energy conversion technologies can use different primary energy forms. For example, Stirling systems can be fueled by diesel or residual oil.

For energy storage technologies, the following requirements are assumed:

- Batteries. Batteries will supply DC power as output. To develop the life-cycle cost and the annual cost of electricity required for charging, a complete charge/discharge cycle is assumed to occur twice per day with a total charge time of 8 hours and a total discharge time of 16 hours. The batteries will operate 365 days per year in a load-leveling mode.

- Thermal Energy Storage. The thermal energy storage devices are assumed to be used for space-heating applications with a continuous diurnal cycle (365 days per year of operation) with a discharge time of 10 hours.

Parameter Definitions

Type. This parameter value is either mobile, transportable, or fixed and refers to the complete energy system, not just the component technology. Mobile, transportable, and fixed are defined as follows:

- A system is mobile if 1) it is transportable by truck or aircraft and 2) can be assembled or dismantled within 8 hours with no prior site preparation. A system is transportable by truck if the system itself or the largest component of the system can be broken down and does not exceed the dimensions of 10 feet wide by 13 feet high by 60 feet long. For air

transportability, the system or largest component of the system cannot exceed 16 feet wide by 9 feet high by 100 feet long, nor can it exceed a weight limit of 350 pounds per square foot floor loading.

- A system is transportable if 1) it is transportable by aircraft subject to the same limitations as mobile and 2) can be set up or removed within 1 week with only minor site preparation.

- A system that is neither mobile nor transportable is fixed.

Fuel Capability. Fuel capability indicates the fuels that can provide the primary energy source for each system. Primary fuels for the purpose of this study include —

- JP-4
- Diesel (DF-1 or DF-2)
- Electricity
- Natural gas
- Solar
- Wind
- Thermal (heat)

Systems that have multifuel capabilities are denoted "multi."

System Acquisition Cost. This is the estimated total installed cost of the energy system excluding land procurement (in 1980 dollars).

Annual Operating and Maintenance Cost. This is the estimated annual cost of operating the energy system (in 1980 dollars). It includes all operating and maintenance expenses except for fuel costs.

System Efficiency:

- Gas Turbines, Diesels, Stirlings, Organic Rankine Cycles, Fuel Cells. The system efficiency is —

  power output ÷ primary fuel energy input rate

  It represents full-load efficiency of new equipment based on higher heating value of the designated fuel, but does not include the energy content of by-product energy recovery unless specifically noted. Efficiency is measured in percent.

- Photovoltaics. System .iciency equals —

(Daily energy productivity) ÷ Daily insolation in plane of collector X Collector area per kW

where —

- Daily energy productivity is 24 kWhr per continuous kW installed capacity. (A one kW system is sized to produce 24 kWhr per day.)

- Daily insolation in the plane of the photovoltaic collector is 1204 Btu/ft^2 day for flat-plate systems, and 1109 Btu/ft^2 day for actively cooled systems.

- Collector area per kW is 783.5 ft^2 for flat-plate systems and 1078 ft^2 for actively cooled photovoltaic systems.

- Wind Turbines. System efficiency equals —

  [System output (kW) at a mean wind speed of 8.1 mph] ÷ [Power in wind at 8.1 mph average wind speed]

- Batteries. System efficiency equals —

  [System energy output] ÷ [System energy input]

Input and output energy is DC power. The AC-to-DC charger efficiency of 90% is reflected in the amount of electricity required to charge the battery system.

- Thermal Energy Storage. System efficiency equals —

  [System thermal energy output] ÷ [Energy required for charging]

Fuel Consumption:

- Gas Turbines, Diesels, Stirlings, Organic Rankine Cycles, Fuel Cells. For energy conversion technologies, fuel consumption is the calculated rate of fuel consumption of the designated fuel divided by the system at its designated output during continuous operation. Fuel consumption is measured in gallons per hour, except for systems fueled by natural gas, which is measured in Btu per hour.

- Photovoltaics and Wind Turbines. These systems have zero fuel consumption.

- Electricity Required for Charging (Batteries). Electricity required for charging is the calculated energy requirement of electricity to obtain 1 kWhr of energy output. Direct current electricity required for charging is measured as $kWhr_{in}$ (into the battery) per $kWhr_{out}$ (delivered to load). The AC-to-DC charger efficiency of 90% is reflected in the amount of electricity required to charge the battery system.

- Annual Energy Required for Charging (Thermal Energy Storage). This is the annual consumption of the designated fuel over its duty cycle of one charging and one discharging period per day (measured in Btu).

Designated Fuel. The fuel on which fuel consumption, annual fuel costs, and life-cycle costs are based.

Annual Fuel Cost:

- Gas Turbines, Diesels, Stirlings, Organic Rankine Cycles, Fuel Cells, Batteries. This is the calculated annual cost of designated fuel: the product of the designated fuel price times the annual fuel consumption of the energy system. Fuels, prices, and energy content are in Table 1. The prices are defined as the worldwide, standard price of fuel from the DFSC stock fund. The prices quoted are based on the average contract prices of fuels in stock plus the average transportation costs to users. Electricity is not included in the DFSC stock fund as a fuel. Electricity costs are subject to regional variations in cost. The cost of electricity in Table 1 is consistent with the U.S. Industrial Price Average for February 1980. Note that the prices in Table 1 are expressed in 1980 dollars with no escalation.

- Photovoltaics, Wind Turbines. The costs of "fuel" for solar and wind powered systems are maintained at zero.

- Thermal Energy Storage: $CaCl_2 \cdot 6H_2O$, $Na_2SO_4 \cdot 10\ H_2O$, $Na_2S_2O_3 \cdot 5H_2O$, Form-Stable Polyethylene. For those thermal energy storage devices where heat is the primary energy, the cost of that heat is assumed to be zero as the cost is implicitly included in the cost of energy from the energy conversion system.

Table 1. FUEL PRICE AND ENERGY CONTENT

Fuel	Fuel Price, 1980 Dollars/Million Btu 1980	1985	1990	2000	Energy Content, Btu/U.S. Gallon
JP-4	8.55	8.82	8.82	8.82	127,500 to 135,714
Diesel	8.40	8.62	8.62	8.62	138,095 to 145,238
Electricity*	1.58	2.79	2.79	2.79	Not Applicable
Natural Gas	2.39	2.47	2.47	2.47	911 to 1012 Btu/SCF

Note: These prices are the cost of fuel into an energy system, not the cost of energy delivered from the system.

* Fuel price in cents per kWhr.

Life-Cycle Cost. The life-cycle cost is the calculated cost of acquiring, operating (including fuel use), and maintaining the energy system at continuous operation at its output level for 20 years. The life-cycle cost is the present value (as of the first year of system operation) of the sum of all system-resultant costs incurred over a 20-year evaluation period. A 20-year, common evaluation period is required to facilitate a direct and valid comparison of the large number of energy conversion systems being considered in this study given their varying service lives, maintenance intervals, and other factors which will affect the amount and timing of system costs. The term "present value" refers to a cash flow that has been adjusted to reflect the interest that could be earned, or must be paid between the time the flow actually occurs and a specified "present" time. A 10% discount rate was used for calculations that reflect the opportunity cost of diverting financial resources from the private to the public sector. This rate is the standard discount rate to be used in evaluating time-distributed costs and benefits for Federal investments, as established in the Office of Management and Budget (OMB) Circular No. A-94. Taxes and depreciation (a noncash expense for offsetting taxes) are, of course, not applicable to Department of Defense cost analyses. Life-cycle-costs are in 1980 dollars per unit of energy output with no real excalation for fuel costs.

The life-cycle cost (LCC) of each system was calculated using the following equation:

$$LCC = PV\ (TIC) + PV\ (AOC) + PV\ (EMC) + PV\ (AFC) + PV\ (FRC)$$

where —

PV = The present value operator (equals 1.0 for TIC, 8.513 for AOC, and 20 for the AFC; dependent on energy conversion technology for EMC and FRC).

TIC = The total installed cost of the energy conversion system including the acquisition cost, the cost of balance of system components, and installation, excluding the cost of land

AOC = The annual operating and maintenance costs, exclusive of fuel, over the 20-year evaluation period

AFC = The annual fuel costs over the 20-year evaluation period (in 1980 dollars with no real escalation)

EMC = any extraordinary (above the normal AOC) maintenance cost which may occur over the 20-year evaluation period (e.g., major overhauls of the

system to extend expected system life to 20 years; or battery replacements)

FRC = the future replacement cost of any components of the energy conversion system, if required during the 20-year evaluation period

Start-up Time (Gas Turbines, Diesels, Organic Rankine Cycles, Fuel Cells, Photovoltaics, Wind Turbines). The start-up time is the elapsed time, in minutes, for the system to achieve full output from a "ready to start" or "cold start" condition.

Shutdown Time (Gas Turbines, Diesels, Organic Rankine Cycles, Fuel Cells, Photovoltaics, Wind Turbines). The shutdown time is the elapsed time, in minutes to bring a system from a full output condition to an off or standby mode.

Charge Time (Batteries, Thermal Energy Storage). The charge time is the nominal elapsed time in minutes for the energy storage system to be fully charged. Faster and slower discharge times are possible.

Discharge Time (Batteries, Thermal Energy Storage). The discharge time is the nominal elapsed time in minutes for the energy storage system to be fully discharged. Faster and slower discharger times are possible.

Volume. This is the volume of the envelope of the installed energy system measured in cubic feet.

Area. This is the land or surface area required for the installed energy system measured in square feet.

Weight. This is the total weight of the complete energy system measured in pounds.

Qualitative Parameters

The qualitative parameters of reliability, environmental constraints, locational constraints, and operational constraints were evaluated in terms of factors that impact the parameters.

Reliability. This is a qualitative parameter that indicates the potential for unanticipated outages of the energy system. Reliability is evaluated in terms of the following factors: moving parts, operating temperature, modularity (redundancy), stress levels, corrosion, and others. Reliability is measured on an ordinal scale:

1. High potential unreliability
2. Moderate potential unreliabilty
3. Average
4. Moderate reliability
5. High reliability.

Environmental Constraints. This is a qualitative parameter that indicates the potential for environmental insult resulting from implementation of the energy system. This parameter is evaluated in terms of the following factors: thermal discharge, air pollution including CO, NO_x, SO_x, HC, particulates, and others; noise; odor; solid waste; and chemical waste. Environmental constraints are measured on an ordinal scale:

1. Extreme potential environmental constraint
2. High potential environmental constraint
3. Average potential environmental constraint
4. Moderate potential environmental constraint
5. Minimum potential environmental constraint

Locational Constraints. This is a qualitative parameter that indicates the potential for locational constraints that could limit the applicability of the energy systems. This parameter is evaluated in terms of the following factors: water requirements, manning requirements, fuel availability, fuel storage, and others (such as solar or wind). Locational constraints are measured on an ordinal scale:

1. Extreme potential locational constraints
2. High potential locational constraints
3. Average locational constraints
4. Moderate locational constraints
5. Minimum locational constraints

Operational Constraints. This is a qualitative parameter that indicates the turn-down and load-following capabilities of the system relative to operating efficiency. This parameter is evaluated in terms of part-load

capability, overload capability, and load-following capability. Operational constraints are measured on an ordinal scale as follows:

1. No turn-down capability
2. Turn-down capability with high efficiency penalty
3. Average turn-down capability
4. Moderate turn-down capability; moderate efficiency penalty
5. Excellent turn-down capability; minor efficiency penalty.

Some of the above parameters were graphed to show trends versus size. So that future technologies could be compared, 1990 values were used in all of these figures. The abbreviation NCA in the tables means Not Commercially Available in that time frame.

TECHNOLOGY DESCRIPTIONS

Diesels

There are three diesel systems of interest in this study: turbocharged, turbocompounded, and adiabatic (Figure 1). Diesels produce shaft power, which is then converted to AC power by an AC generator. Turbocompounded diesels should be more efficient than turbocharged diesels because of the additional shaft power derived from the exhaust-gas driven turbine. Adiabatic diesels operate at higher pressures and temperatures than the turbocompounded and turbocharged systems. (The adiabatic is not cooled.) Because of the higher pressure and temperature operation, overall system efficiency is expected to be greater for the adiabatic diesel than for the turbocompounded. The system may also be lighter and more reliable by the elimination of the cooling system.

Diesel generators are typically used as back-up systems for utility-supplied power or in remote locations without a utility power grid. They operate in continuous or intermittent service. As previously mentioned, the data presented here are for continuous operation (365 days per year at 24 hours per day less 10% of that time for scheduled maintenance) producing utility-quality power.

Technology Status. Turbocompounded diesels will be commercially available in capacities greater or equal to 100.0 kW starting in 1985. Turbocharged diesels are current technology and are currently commercially available in capacities greater or equal to 5.0 kW. Adiabatic diesels will be commercially available in capacities greater or equal to 125.0 kW starting in 1990. The major constraint of the adiabatic diesel is the need to develop composite ceramic/metal structures consistent with the 1800°F operating temperature.

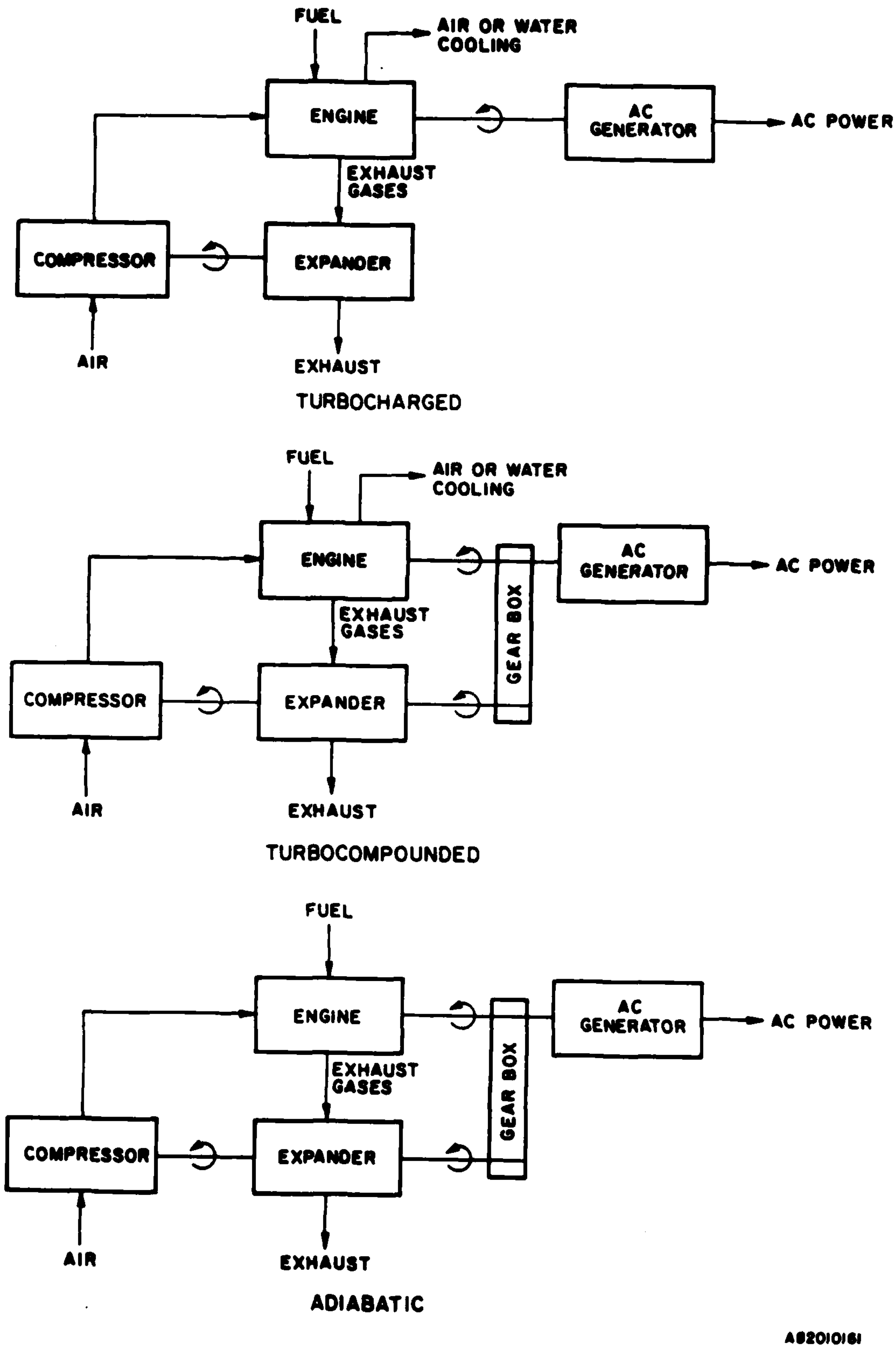

Figure 1. DIESEL SYSTEMS

Type. Most diesels are mobile up to the megawatt sizes, which are transportable (Table 2).

Table 2. DIESEL TYPE (Mobile or Transportable)

POWER OUTPUT LEVEL, KW	YEAR	TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	M	NCA
	1985	NCA	M	NCA
	1990	NCA	M	NCA
	2000	NCA	M	NCA
20.0	1980	NCA	M	NCA
	1985	NCA	M	NCA
	1990	NCA	M	NCA
	2000	NCA	M	NCA
30.0	1980	NCA	M	NCA
	1985	NCA	M	NCA
	1990	NCA	M	NCA
	2000	NCA	M	NCA
60.0	1980	NCA	M	NCA
	1985	NCA	M	NCA
	1990	NCA	M	NCA
	2000	NCA	M	NCA
100.0	1980	NCA	M	NCA
	1985	M	M	NCA
	1990	M	M	NCA
	2000	M	M	NCA
250.0	1980	NCA	M	NCA
	1985	M	M	NCA
	1990	M	M	M
	2000	M	M	M
500.0	1980	NCA	M	NCA
	1985	M	M	NCA
	1990	M	M	M
	2000	M	M	M
750.0	1980	NCA	M	NCA
	1985	M	M	NCA
	1990	M	M	M
	2000	M	M	M
1000.0	1980	NCA	T	NCA
	1985	T	T	NCA
	1990	T	T	T
	2000	T	T	T
5000.0	1980	NCA	T	NCA
	1985	T	T	NCA
	1990	T	T	T
	2000	T	T	T

__System Acquisition Cost.__ Diesel "System Acquisition Cost" parameter values are presented in Table 3 and in Figure 2 in 1980 dollars as a function of size.

Table 3. DIESEL SYSTEM ACQUISITION COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	4.82E03	NCA
	1985	NCA	4.82E03	NCA
	1990	NCA	5.30E03	NCA
	2000	NCA	5.30E03	NCA
20.0	1980	NCA	2.32E04	NCA
	1985	NCA	2.32E04	NCA
	1990	NCA	2.55E04	NCA
	2000	NCA	2.55E04	NCA
30.0	1980	NCA	3.88E04	NCA
	1985	NCA	3.88E04	NCA
	1990	NCA	4.27E04	NCA
	2000	NCA	4.27E04	NCA
60.0	1980	NCA	1.01E05	NCA
	1985	NCA	1.01E05	NCA
	1990	NCA	1.11E05	NCA
	2000	NCA	1.11E05	NCA
100.0	1980	NCA	2.22E05	NCA
	1985	3.55E05	2.22E05	NCA
	1990	3.91E05	2.44E05	NCA
	2000	3.91E05	2.44E05	NCA
250.0	1980	NCA	4.80E05	NCA
	1985	7.68E05	4.80E05	NCA
	1990	8.45E05	5.28E05	7.61E05
	2000	8.45E05	5.28E05	7.61E05
500.0	1980	NCA	8.46E05	NCA
	1985	1.35E06	8.46E05	NCA
	1990	1.49E06	9.31E05	1.34E06
	2000	1.49E06	9.31E05	1.34E06
750.0	1980	NCA	1.17E06	NCA
	1985	1.87E06	1.17E06	NCA
	1990	2.06E06	1.29E06	1.83E06
	2000	2.06E06	1.29E06	1.83E06
1000.0	1980	NCA	1.47E06	NCA
	1985	2.35E06	1.47E06	NCA
	1990	2.59E06	1.62E06	2.33E06
	2000	2.59E06	1.62E06	2.33E06
5000.0	1980	NCA	4.70E06	NCA
	1985	7.52E06	4.70E06	NCA
	1990	8.27E06	5.17E06	7.45E06
	2000	8.27E06	5.17E06	7.45E06

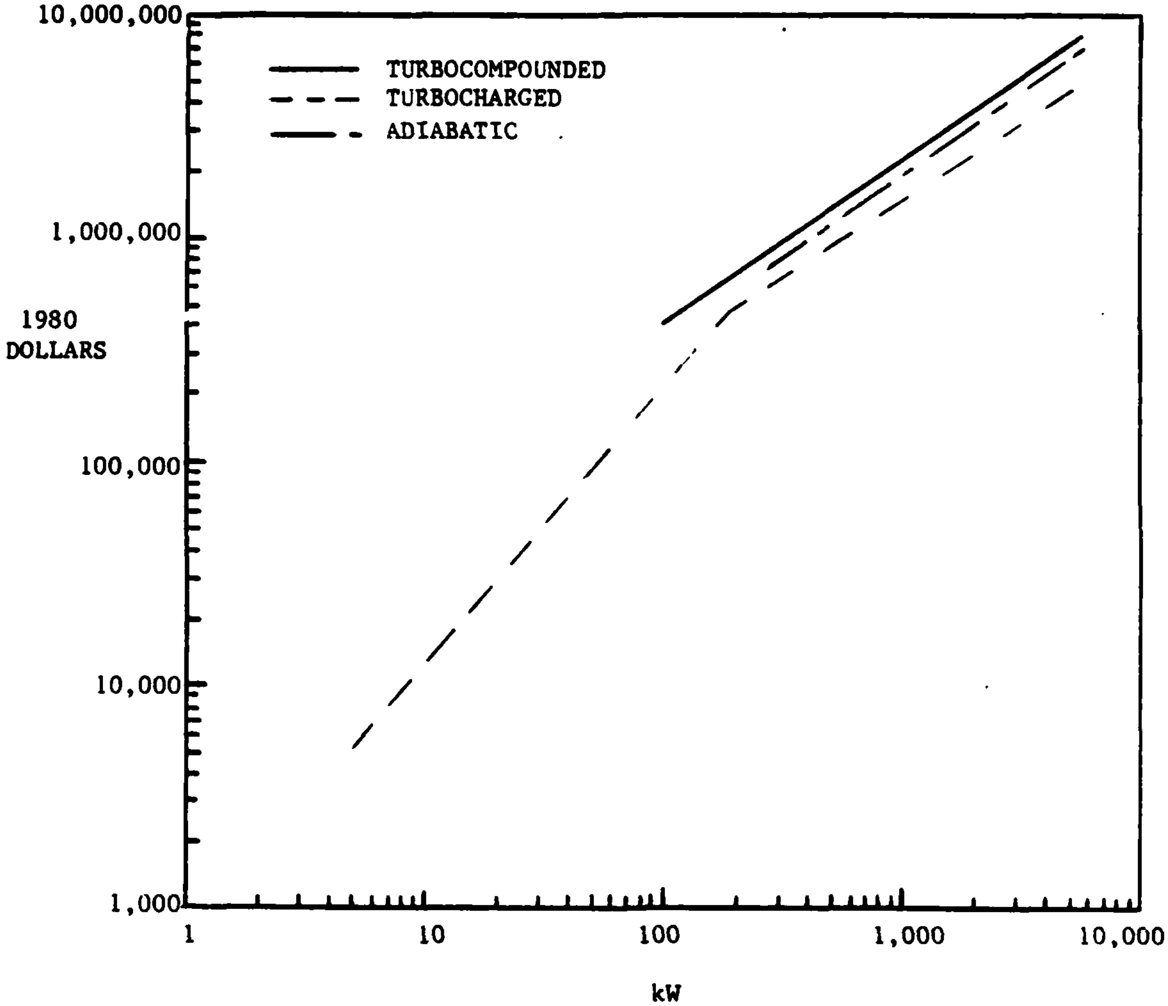

Figure 2. DIESEL SYSTEM ACQUISITION COST

Annual Operations and Maintenance Costs. Diesel "Annual Operations and Maintenance Costs" parameter values are presented in Table 4 and in Figure 3.

Table 4. DIESEL ANNUAL OPERATIONS AND MAINTENANCE COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	1.21E02	NCA
	1985	NCA	1.21E02	NCA
	1990	NCA	1.33E02	NCA
	2000	NCA	1.33E02	NCA
20.0	1980	NCA	3.78E02	NCA
	1985	NCA	3.78E02	NCA
	1990	NCA	4.16E02	NCA
	2000	NCA	4.16E02	NCA
30.0	1980	NCA	5.47E02	NCA
	1985	NCA	5.47E02	NCA
	1990	NCA	6.02E02	NCA
	2000	NCA	6.02E02	NCA
60.0	1980	NCA	1.10E03	NCA
	1985	NCA	1.10E03	NCA
	1990	NCA	1.21E03	NCA
	2000	NCA	1.21E03	NCA
100.0	1980	NCA	2.03E03	NCA
	1985	3.25E03	2.03E03	NCA
	1990	3.58E03	2.23E03	NCA
	2000	3.58E03	2.23E03	NCA
250.0	1980	NCA	3.65E03	NCA
	1985	5.84E03	3.65E03	NCA
	1990	6.42E03	4.01E03	5.78E03
	2000	6.41E03	4.01E03	5.78E03
500.0	1980	NCA	7.08E03	NCA
	1985	1.13E04	7.08E03	NCA
	1990	1.24E04	7.79E03	1.12E04
	2000	1.24E04	7.79E03	1.12E04
750.0	1980	NCA	1.16E04	NCA
	1985	1.85E04	1.16E04	NCA
	1990	2.03E04	1.27E04	1.80E04
	2000	2.03E04	1.27E04	1.80E04
1000.0	1980	NCA	1.71E04	NCA
	1985	2.74E04	1.71E04	NCA
	1990	3.01E04	1.88E04	2.71E04
	2000	3.01E04	1.88E04	2.71E04
5000.0	1980	NCA	1.84E05	NCA
	1985	2.95E05	1.84E05	NCA
	1990	3.24E05	2.03E05	2.92E05
	2000	3.24E05	2.03E05	2.92E05

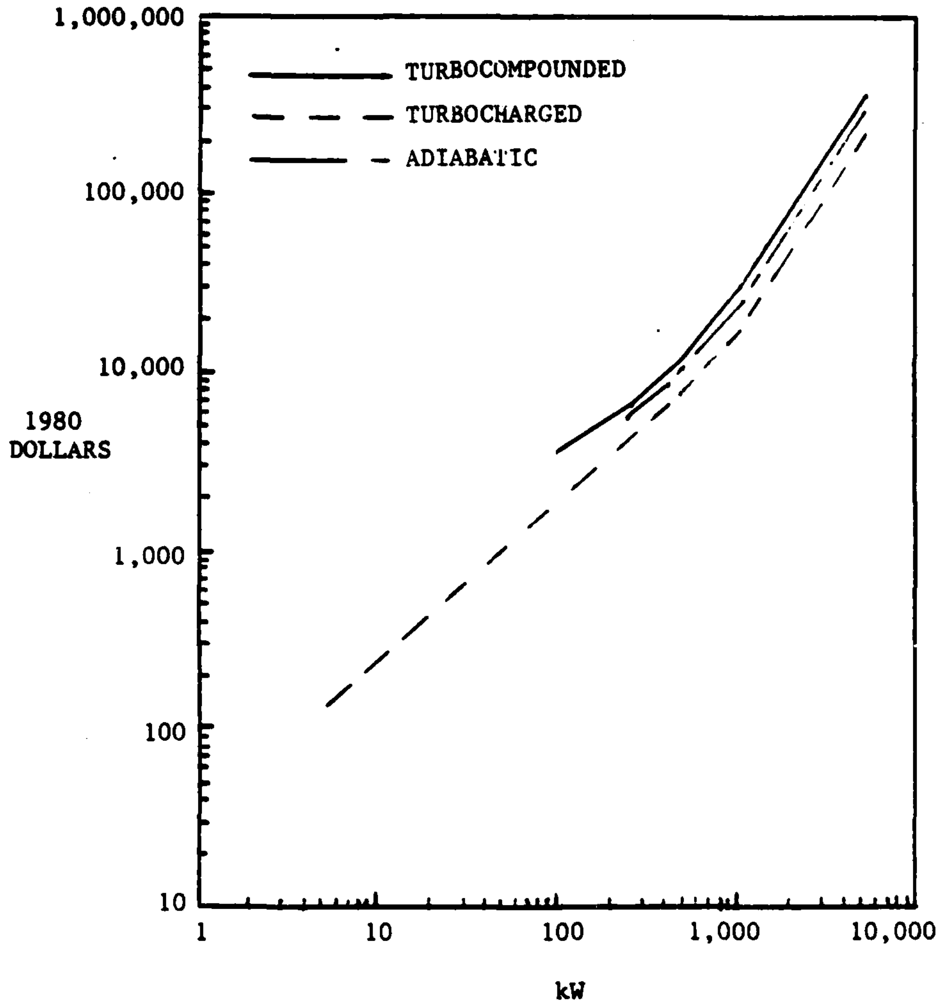

Figure 3. DIESEL ANNUAL OPERATIONS
AND MAINTENANCE COSTS

System Efficiency. Diesel system efficiency tends to increase as the system power level (size) increases (Table 5 and Figure 4).

Table 5. DIESEL SYSTEM EFFICIENCY (%)

POWER OUTPUT LEVEL, KW	YEAR	TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	26.9	NCA
	1985	NCA	29.6	NCA
	1990	NCA	31.1	NCA
	2000	NCA	31.1	NCA
20.0	1980	NCA	29.0	NCA
	1985	NCA	32.0	NCA
	1990	NCA	33.6	NCA
	2000	NCA	33.6	NCA
30.0	1980	NCA	29.5	NCA
	1985	NCA	32.5	NCA
	1990	NCA	34.1	NCA
	2000	NCA	34.1	NCA
60.0	1980	NCA	30.6	NCA
	1985	NCA	33.7	NCA
	1990	NCA	35.4	NCA
	2000	NCA	35.4	NCA
100.0	1980	NCA	31.3	NCA
	1985	40.7	34.5	NCA
	1990	42.7	36.2	46.2
	2000	42.7	36.2	46.2
250.0	1980	NCA	32.7	NCA
	1985	42.5	36.0	NCA
	1990	44.6	37.8	47.8
	2000	44.6	37.8	47.8
500.0	1980	NCA	33.7	NCA
	1985	43.8	37.1	NCA
	1990	46.0	39.0	48.0
	2000	46.0	39.0	48.0
750.0	1980	NCA	34.3	NCA
	1985	44.6	37.8	NCA
	1990	46.8	39.7	48.7
	2000	46.8	39.7	48.7
1000.0	1980	NCA	34.7	NCA
	1985	45.1	38.2	NCA
	1990	47.3	40.1	49.1
	2000	47.3	40.1	49.1
5000.0	1980	NCA	37.0	NCA
	1985	48.1	40.8	NCA
	1990	50.5	42.8	51.8
	2000	50.5	42.8	51.8

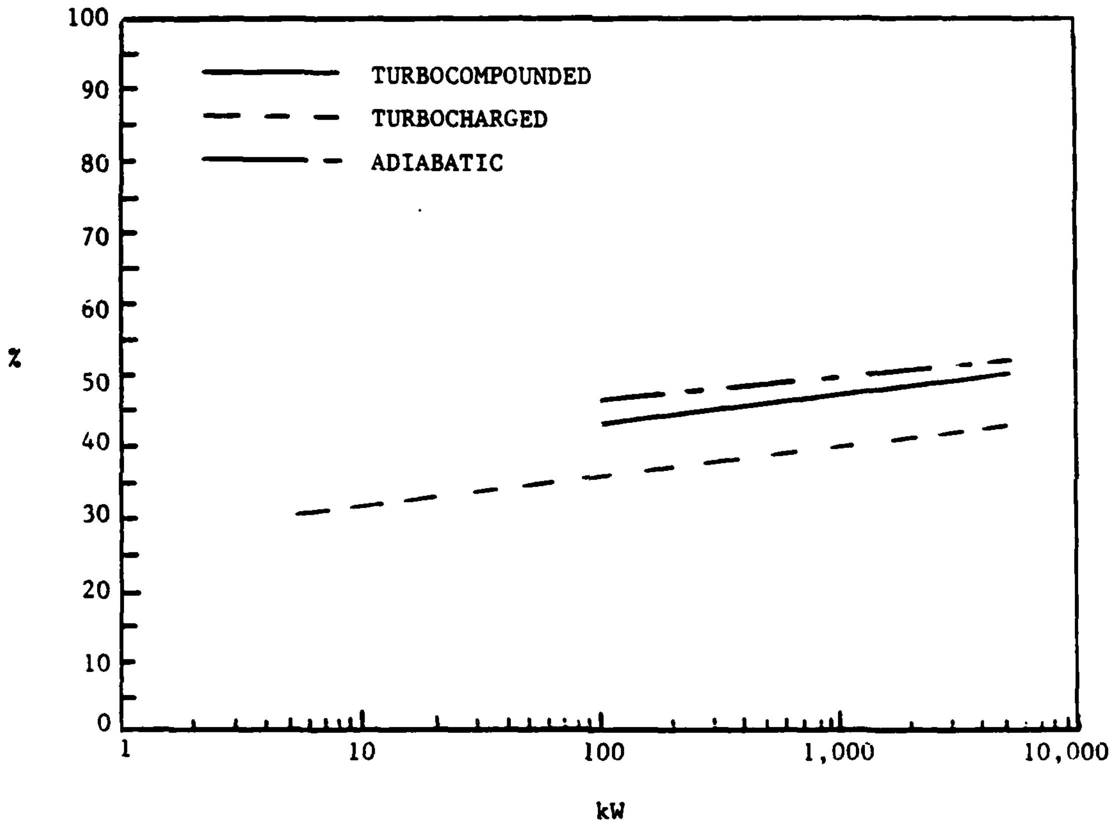

Figure 4. DIESEL SYSTEM EFFICIENCY

Fuel Consumption. Diesel "Fuel Consumption" parameters values are presented in Table 6 and Figure 5. Typically, diesels are fueled with DF-1 or DF-2, but some manufacturers in Europe (for example, Stal Laval) are developing diesels for residual fuel. Because of the price differential this would tend to decrease the life-cycle cost of diesel systems. (Residual is about $5.85/million Btu; DF-1 and DF-2 are about $8.62/million Btu.)

Table 6. DIESEL FUEL CONSUMPTION

POWER OUTPUT LEVEL, KW	YEAR	gal/hr TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	0.45	NCA
	1985	NCA	0.41	NCA
	1990	NCA	0.39	NCA
	2000	NCA	0.39	NCA
20.0	1980	NCA	1.66	NCA
	1985	NCA	1.51	NCA
	1990	NCA	1.43	NCA
	2000	NCA	1.43	NCA
30.0	1980	NCA	2.45	NCA
	1985	NCA	2.24	NCA
	1990	NCA	2.12	NCA
	2000	NCA	2.12	NCA
60.0	1980	NCA	4.74	NCA
	1985	NCA	4.29	NCA
	1990	NCA	4.09	NCA
	2000	NCA	4.09	NCA
100.0	1980	NCA	7.71	NCA
	1985	5.93	6.99	NCA
	1990	5.65	6.66	NCA
	2000	5.65	6.66	NCA
250.0	1980	NCA	18.5	NCA
	1985	14.8	16.7	NCA
	1990	14.1	15.9	12.7
	2000	14.1	15.9	12.7
500.0	1980	NCA	35.7	NCA
	1985	28.4	32.5	NCA
	1990	26.3	30.9	25.1
	2000	26.3	30.9	25.1
750.0	1980	NCA	52.8	NCA
	1985	40.5	47.8	NCA
	1990	38.7	45.6	37.2
	2000	38.7	45.6	37.2
1000.0	1980	NCA	69.6	NCA
	1985	53.5	63.2	NCA
	1990	50.9	60.1	49.1
	2000	50.9	60.1	49.1
5000.0	1980	NCA	326	NCA
	1985	251	295	NCA
	1990	239	283	233
	2000	239	283	233

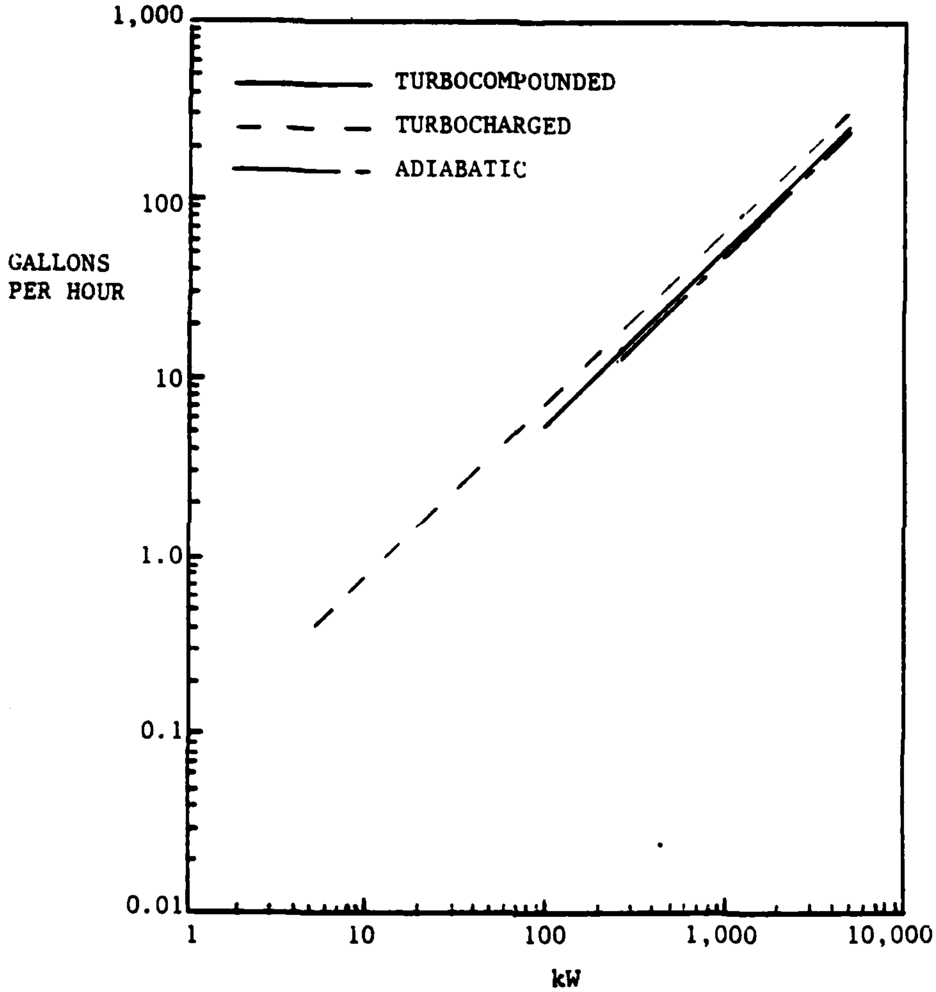

Figure 5. DIESEL FUEL CONSUMPTION

Annual Fuel Cost. Diesel "Annual Fuel Cost" parameter values, based on 1980 dollars and no real escalation, are presented in Table 7 and in Figure 6.

Table 7. DIESEL ANNUAL FUEL COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	4.20E03	NCA
	1985	NCA	3.92E03	NCA
	1990	NCA	3.73E03	NCA
	2000	NCA	3.73E03	NCA
20.0	1980	NCA	1.56E04	NCA
	1985	NCA	1.45E04	NCA
	1990	NCA	1.38E04	NCA
	2000	NCA	1.38E04	NCA
30.0	1980	NCA	2.30E04	NCA
	1985	NCA	2.15E04	NCA
	1990	NCA	2.04E04	NCA
	2000	NCA	2.04E04	NCA
60.0	1980	NCA	4.44E04	NCA
	1985	NCA	4.13E04	NCA
	1990	NCA	3.93E04	NCA
	2000	NCA	3.93E04	NCA
100.0	1980	NCA	7.22E04	NCA
	1985	5.70E04	6.72E04	NCA
	1990	5.43E04	6.41E04	NCA
	2000	5.43E04	6.41E04	NCA
250.0	1980	NCA	1.73E05	NCA
	1985	1.42E05	1.61E05	NCA
	1990	1.36E05	1.53E05	1.22E05
	2000	1.36E05	1.53E05	1.22E05
500.0	1980	NCA	3.35E05	NCA
	1985	2.73E05	3.13E05	NCA
	1990	2.53E05	2.97E05	2.41E05
	2000	2.53E05	2.97E05	2.41E05
750.0	1980	NCA	4.95E05	NCA
	1985	3.90E05	4.60E05	NCA
	1990	3.72E05	4.39E05	3.58E05
	2000	3.72E05	4.39E05	3.58E05
1000.0	1980	NCA	6.52E05	NCA
	1985	5.15E05	6.08E05	NCA
	1990	4.90E05	5.78E05	4.72E05
	2000	4.90E05	5.78E05	4.72E05
5000.0	1980	NCA	3.06E06	NCA
	1985	2.41E06	2.84E06	NCA
	1990	2.30E06	2.72E06	2.24E06
	2000	2.30E06	2.72E06	2.24E06

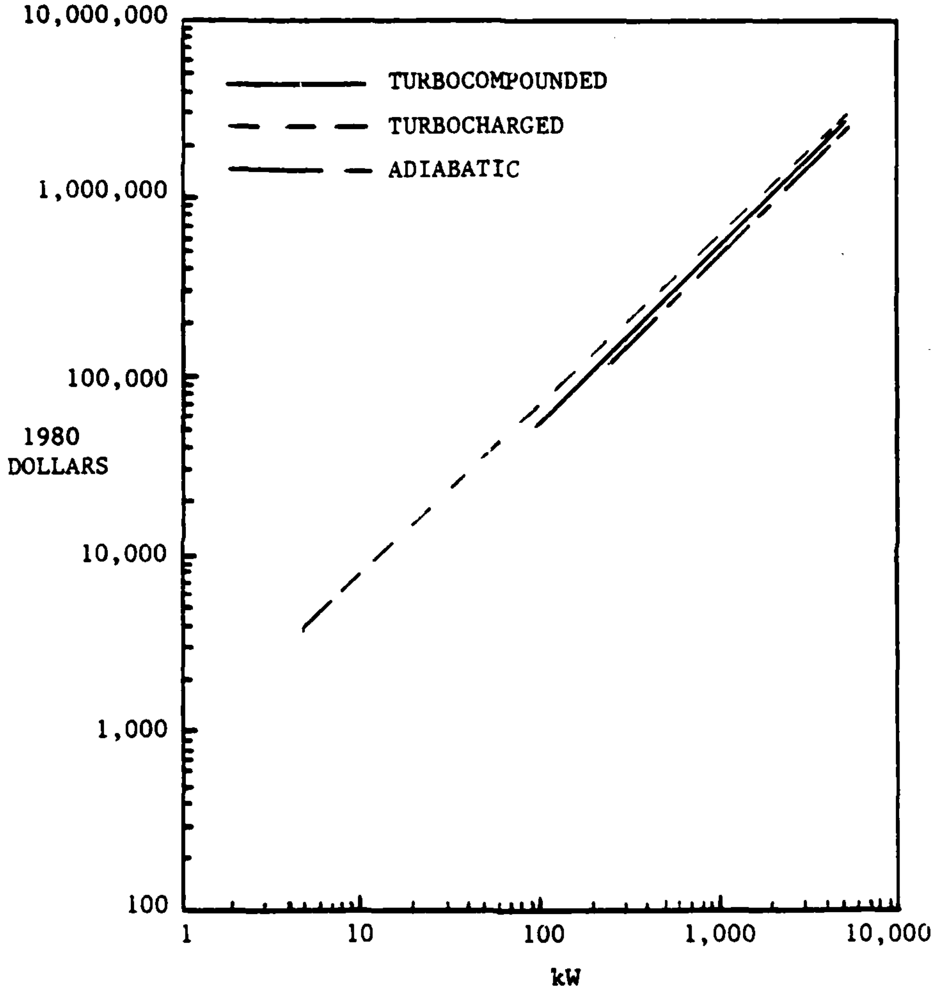

Figure 6. DIESEL ANNUAL FUEL COST

<u>Life-Cycle Cost</u>. Diesel "Life-Cycle Cost" parameter values are presented in Table 8 and Figure 7.

Table 8. DIESEL LIFE-CYCLE COSTS (1980 cents/kW)

POWER OUTPUT LEVEL, KW	YEAR	TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	5.28	NCA
	1985	NCA	4.97	NCA
	1990	NCA	4.84	NCA
	2000	NCA	4.84	NCA
20.0	1980	NCA	5.05	NCA
	1985	NCA	4.75	NCA
	1990	NCA	4.65	NCA
	2000	NCA	4.65	NCA
30.0	1980	NCA	5.06	NCA
	1985	NCA	4.79	NCA
	1990	NCA	4.68	NCA
	2000	NCA	4.68	NCA
60.0	1980	NCA	5.16	NCA
	1985	NCA	4.88	NCA
	1990	NCA	4.82	NCA
	2000	NCA	4.82	NCA
100.0	1980	NCA	5.42	NCA
	1985	5.50	5.15	NCA
	1990	5.60	5.13	NCA
	2000	5.60	5.13	NCA
250.0	1980	NCA	5.03	NCA
	1985	5.14	4.77	NCA
	1990	5.22	4.73	4.69
	2000	5.22	4.73	4.69
500.0	1980	NCA	4.77	NCA
	1985	4.78	4.53	NCA
	1990	4.76	4.47	4.42
	2000	4.76	4.47	4.42
750.0	1980	NCA	4.64	NCA
	1985	4.52	4.38	NCA
	1990	4.57	4.34	4.25
	2000	4.57	4.34	4.25
1000.0	1980	NCA	4.54	NCA
	1985	4.42	4.31	NCA
	1990	4.45	4.25	4.17
	2000	4.45	4.25	4.17
5000.0	1980	NCA	4.10	NCA
	1985	3.87	3.86	NCA
	1990	3.88	3.81	3.68
	2000	3.88	3.81	3.68

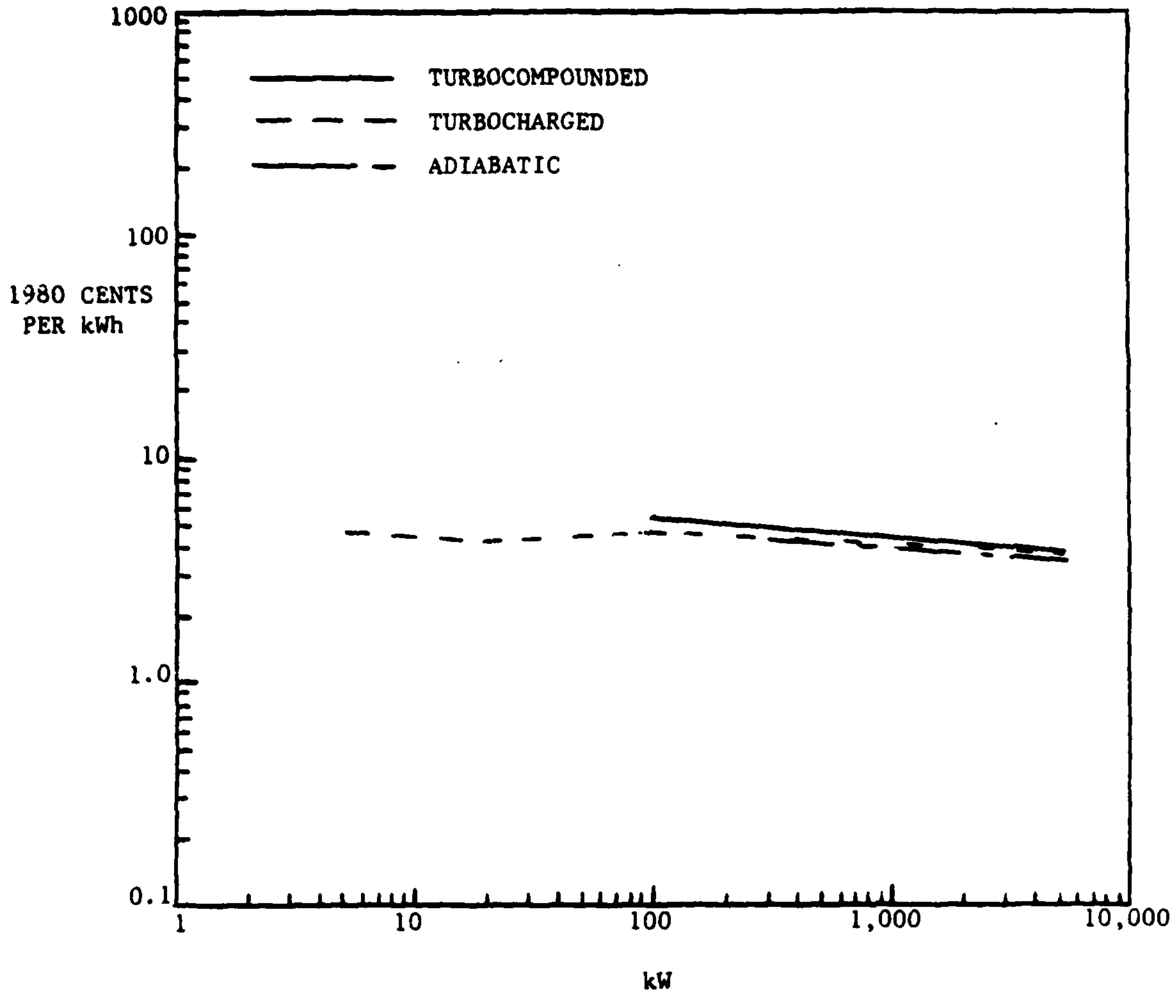

Figure 7. DIESEL LIFE-CYCLE COST

System Volume. Diesel "System Volume" parameter values are presented in Table 9 below.

Table 9. DIESEL SYSTEM VOLUME (CUBIC FEET)

POWER OUTPUT LEVEL, KW	YEAR	TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	1.55E01	NCA
	1985	NCA	1.55E01	NCA
	1990	NCA	1.55E01	NCA
	2000	NCA	1.55E01	NCA
20.0	1980	NCA	4.02E01	NCA
	1985	NCA	4.02E01	NCA
	1990	NCA	4.02E01	NCA
	2000	NCA	4.02E01	NCA
30.0	1980	NCA	5.24E01	NCA
	1985	NCA	5.24E01	NCA
	1990	NCA	5.24E01	NCA
	2000	NCA	5.24E01	NCA
60.0	1980	NCA	8.11E01	NCA
	1985	NCA	8.11E01	NCA
	1990	NCA	8.11E01	NCA
	2000	NCA	8.11E01	NCA
100.0	1980	NCA	1.11E02	NCA
	1985	1.11E02	1.11E02	NCA
	1990	1.11E02	1.11E02	NCA
	2000	1.11E02	1.11E02	NCA
250.0	1980	NCA	1.91E02	NCA
	1985	1.91E02	1.91E02	NCA
	1990	1.91E02	1.91E02	1.72E02
	2000	1.91E02	1.91E02	1.72E02
500.0	1980	NCA	2.93E02	NCA
	1985	2.93E02	2.93E02	NCA
	1990	2.93E02	2.93E02	2.63E02
	2000	2.93E02	2.93E02	2.63E02
750.0	1980	NCA	3.87E02	NCA
	1985	3.87E02	3.87E02	NCA
	1990	3.87E02	3.87E02	3.48E02
	2000	3.87E02	3.87E02	3.48E02
1000.0	1980	NCA	4.81E02	NCA
	1985	4.81E02	4.81E01	NCA
	1990	4.81E02	4.81E02	4.33E02
	2000	4.81E02	4.81E02	4.33E02
5000.0	1980	NCA	2.57E03	NCA
	1985	2.57E03	2.57E03	NCA
	1990	2.57E03	2.57E03	2.31E03
	2000	2.57E03	2.57E03	2.31E03

System Weight. Diesel "System Weight" parameter values are presented in Table 10.

Table 10. DIESEL SYSTEM WEIGHT (POUNDS)

POWER OUTPUT LEVEL, KW	YEAR	TURBO-COMPOUNDED	TURBO-CHARGED	ADIABATIC
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	9.84E02	NCA
	1985	NCA	9.84E02	NCA
	1990	NCA	9.84E02	NCA
	2000	NCA	9.84E02	NCA
20.0	1980	NCA	2.03E03	NCA
	1985	NCA	2.03E03	NCA
	1990	NCA	2.03E03	NCA
	2000	NCA	2.03E03	NCA
30.0	1980	NCA	2.65E03	NCA
	1985	NCA	2.65E03	NCA
	1990	NCA	2.65E03	NCA
	2000	NCA	2.65E03	NCA
60.0	1980	NCA	4.10E03	NCA
	1985	NCA	4.10E03	NCA
	1990	NCA	4.10E03	NCA
	2000	NCA	4.10E03	NCA
100.0	1980	NCA	5.61E03	NCA
	1985	5.61E03	5.61E03	NCA
	1990	5.61E03	5.61E03	NCA
	2000	5.61E03	5.61E03	NCA
250.0	1980	NCA	9.74E03	NCA
	1985	9.74E03	9.74E03	NCA
	1990	9.74E03	9.74E03	8.78E03
	2000	9.74E03	9.74E03	8.78E03
500.0	1980	NCA	1.51E04	NCA
	1985	1.51E04	1.51E04	NCA
	1990	1.51E04	1.51E04	1.36E04
	2000	1.51E04	1.51E04	1.36E04
750.0	1980	NCA	2.01E04	NCA
	1985	2.01E04	2.01E04	NCA
	1990	2.01E04	2.01E04	1.81E04
	2000	2.01E04	2.01E04	1.81E04
1000.0	1980	NCA	2.52E04	NCA
	1985	2.52E04	2.52E04	NCA
	1990	2.52E04	2.52E04	2.27E04
	2000	2.52E04	2.52E04	2.27E04
5000.0	1980	NCA	1.38E05	NCA
	1985	1.38E05	1.38E05	NCA
	1990	1.38E05	1.38E05	1.24E05
	2000	1.38E05	1.38E05	1.24E05

Fuel Requirements and Capabilities. Diesels are primarily fueled with DF-1 or DF-2, although some have the capability for residual or DF-A. The designated fuel is "Diesel."

Start-up Time. Diesel "Start-up Time" ranges from 1 to 3 minutes A typical value is 2 minutes.

Shutdown Time. Diesel "Shutdown Time" is 2 seconds.

Reliability. Diesel "reliability" has an ordinal score of 3 indicating average reliability because diesel systems contain numerous moving parts, operate at moderately high temperatures, and cycle thermally.

Environmental Constraints. Diesels have an ordinal score of 4 for "Environmental Constraints," which indicates moderate potential environmental insult because of toxic exhaust emissions, noise during operation, and discharge of significant thermal energy.

Location Constraints. Diesels have an ordinal score of 3 indicating average locational constraints because of fuel availability, delivery, and storage requirements.

Operation Constraints. Diesels have an ordinal score of 4 indicating moderate turn-down capability with moderate efficiency penalty. Efficiency and lifetimes are adversely affected by changing loads.

Gas Turbines

There are three gas turbine systems of interest in this study: open-cycle nonrecuperative, open-cycle recuperative, and closed cycles (Figure 8). Gas turbines produce shaft power, which is then converted to AC power by an AC generator. Because the closed-cycle system uses a working fluid rather than combustion products, it can be operated on alternative primary fuels, including residual oil.

Technology Status. Regenerative open-cycle gas turbine systems will be commercially available in capacities of 1000.0 kW and 500.0 kW starting in 1985. They will be commercially available in capacities greater or equal to 100.0 kW starting in 1990. Closed-cycle gas turbine systems will be commercially available in capacities greater or equal to 1000.0 kW in 1985. Non-regenerative open-cycle gas turbines are commercially available in capacities greater or equal to 500.0 kW. They will be commercially available at capacities of 100.0 and 250.0 kW in 1990. They will be commercially available at a capacity of 60.0 kW in 2000.

Development of the closed-cycle gas turbine is constrained by the need for an effective high-temperature heat exchanger.

Scaling down the turbines is a question of the capability to competitively produce high speed rotating equipment that would provide less flow resistance relative to the larger turbine/turbocompressor rotors. For small machines the rotors would have to be of the radial (rather than axial) type.

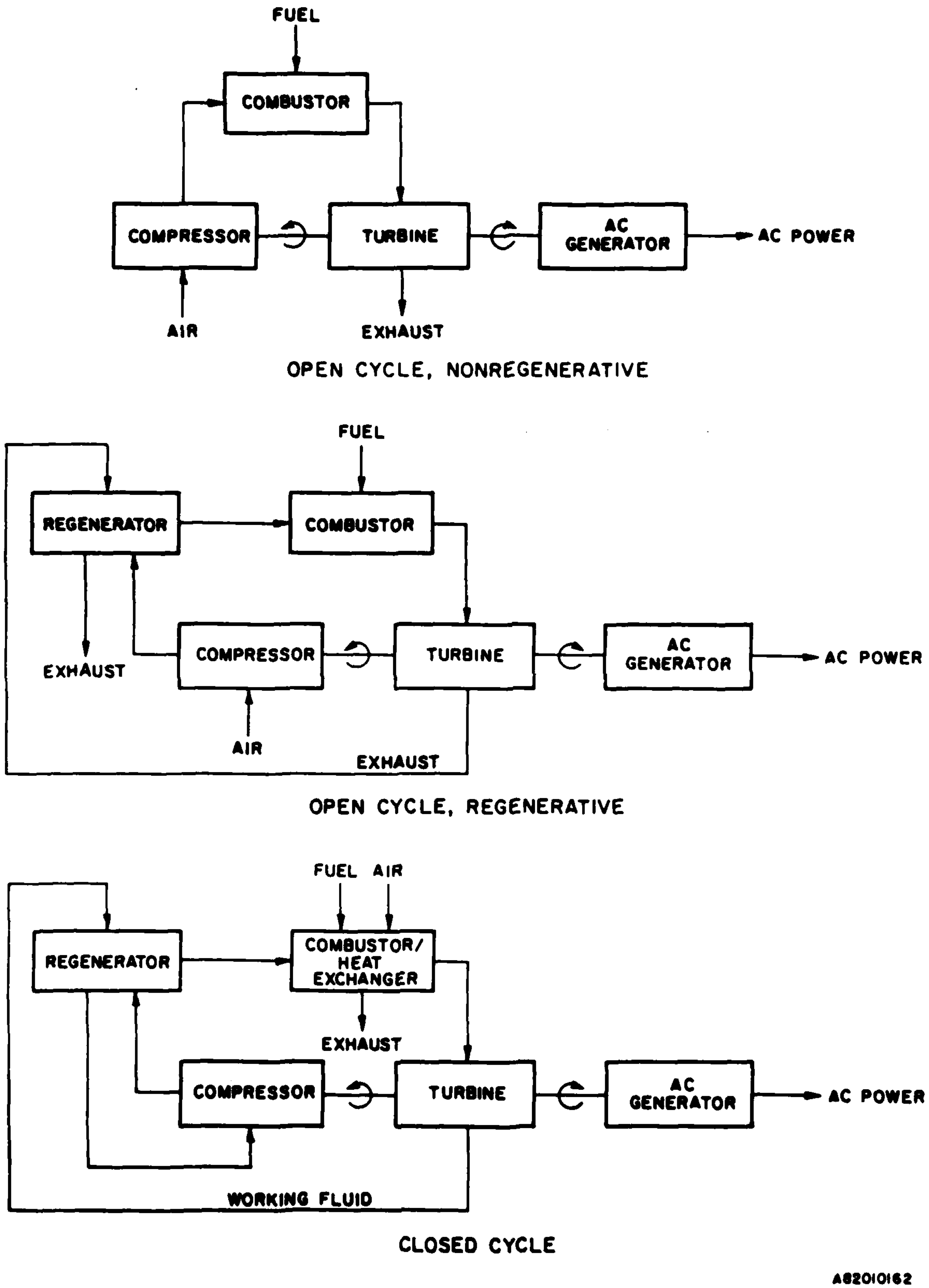

Figure 8. GAS TURBINE SYSTEMS

Type. Gas turbine systems are generally mobile at size below 750 kW and transportable in the megawatt sizes (Table 11).

Table 11. GAS TURBINE SYSTEM TYPE
(Mobile, Transportable)

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE	CLOSED CYCLE	NON-REGENERATIVE OPEN-CYCLE
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	M
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	M	NCA	M
	2000	M	NCA	M
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	M	NCA	M
	2000	M	NCA	M
500.0	1980	NCA	NCA	M
	1985	NCA	NCA	M
	1990	M	NCA	M
	2000	M	NCA	M
750.0	1980	NCA	NCA	M
	1985	NCA	NCA	M
	1990	T	NCA	M
	2000	T	NCA	M
1000.0	1980	NCA	NCA	T
	1985	T	T	T
	1990	T	T	T
	2000	T	T	T
5000.0	1980	T	NCA	T
	1985	T	T	T
	1990	T	T	T
	2000	T	T	T

System Acquisition Cost. Gas turbine "System Acquisition Cost" parameter values are presented in Table 12 and in Figure 9 in 1980 dollars as a function of size.

Table 12. GAS TURBINE SYSTEM ACQUISITION COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE	CLOSED CYCLE	NON-REGENERATIVE OPEN-CYCLE
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	4.11E04
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	6.36E04	NCA	6.06E04
	2000	6.36E04	NCA	6.06E04
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.28E05	NCA	1.22E05
	2000	1.28E05	NCA	1.22E05
500.0	1980	NCA	NCA	2.06E05
	1985	NCA	NCA	2.06E05
	1990	2.16E05	NCA	2.06E05
	2000	2.16E05	NCA	2.06E05
750.0	1980	NCA	NCA	2.81E05
	1985	NCA	NCA	2.81E05
	1990	2.95E05	NCA	2.81E05
	2000	2.95E05	NCA	2.81E05
1000.0	1980	NCA	NCA	3.50E05
	1985	3.68E05	3.85E05	3.50E05
	1990	3.68E05	3.85E05	3.50E05
	2000	3.68E05	3.85E05	3.50E05
5000.0	1980	1.26E06	NCA	1.20E06
	1985	1.26E06	1.32E06	1.20E06
	1990	1.26E06	1.32E06	1.20E06
	2000	1.26E06	1.32E06	1.20E06

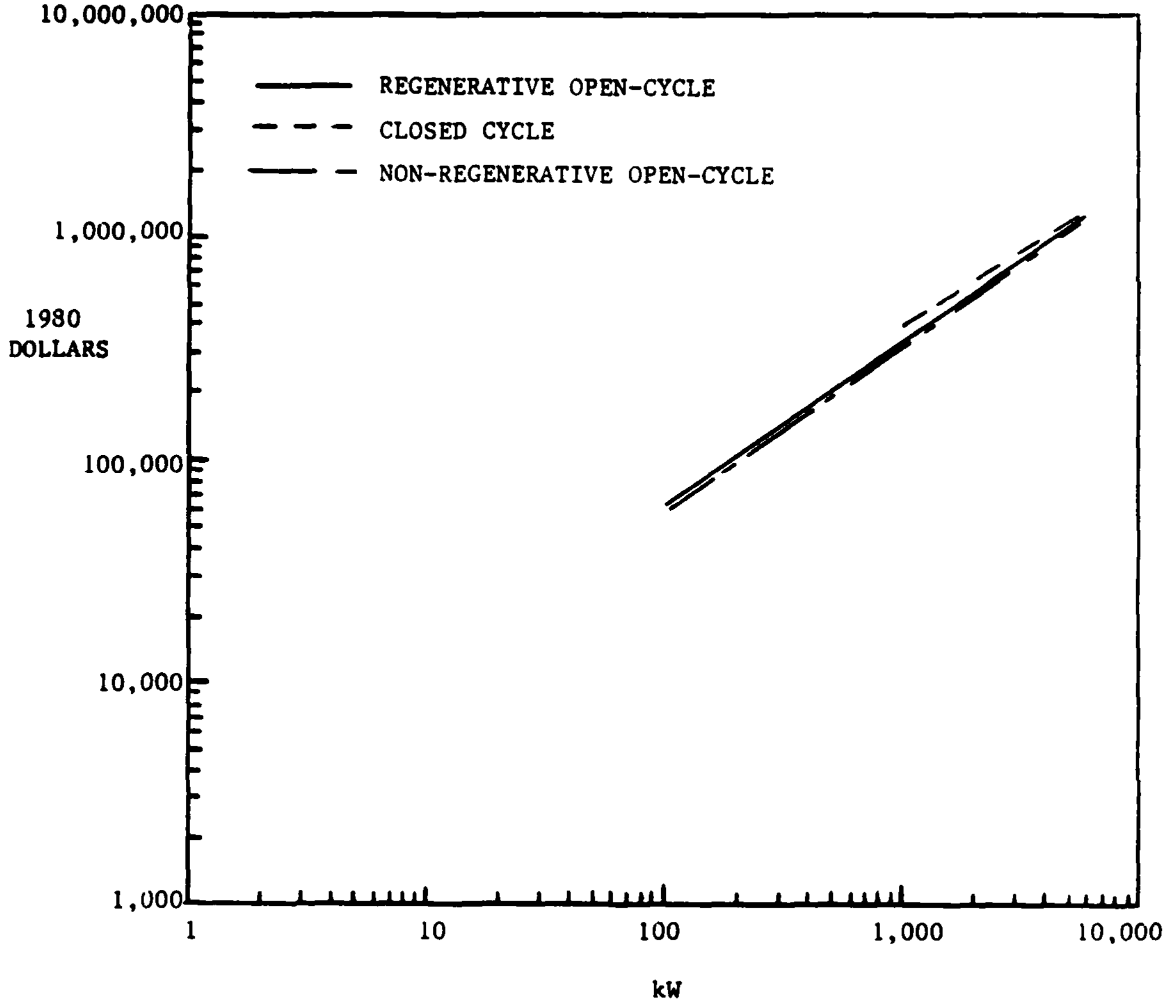

Figure 9. GAS TURBINE SYSTEM ACQUISITION COST

Annual Operations and Maintenance Costs. Gas turbine "Annual Operations and Maintenance Costs" parameter values are presented in Table 13 and in Figure 10.

Table 13. GAS TURBINE ANNUAL OPERATIONS AND MAINTENANCE COSTS (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE	CLOSED CYCLE	NON-REGENERATIVE OPEN-CYCLE
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	2.05E03
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.18E03	NCA	3.03E03
	2000	3.18E03	NCA	3.03E03
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	6.40E03	NCA	6.09E03
	2000	6.40E03	NCA	6.09E03
500.0	1980	NCA	NCA	1.03E04
	1985	NCA	NCA	1.03E04
	1990	1.08E04	NCA	1.03E04
	2000	1.08E04	NCA	1.03E04
750.0	1980	NCA	NCA	1.41E04
	1985	NCA	NCA	1.41E04
	1990	1.48E04	NCA	1.41E04
	2000	1.48E04	NCA	1.41E04
1000.0	1980	NCA	NCA	1.75E04
	1985	1.85E04	1.93E04	1.75E04
	1990	1.85E04	1.93E04	1.75E04
	2000	1.85E04	1.93E04	1.75E04
5000.0	1980	6.08E04	NCA	5.97E04
	1985	6.08E04	6.37E04	5.97E04
	1990	6.08E04	6.37E04	5.97E04
	2000	6.08E04	6.37E04	5.97E04

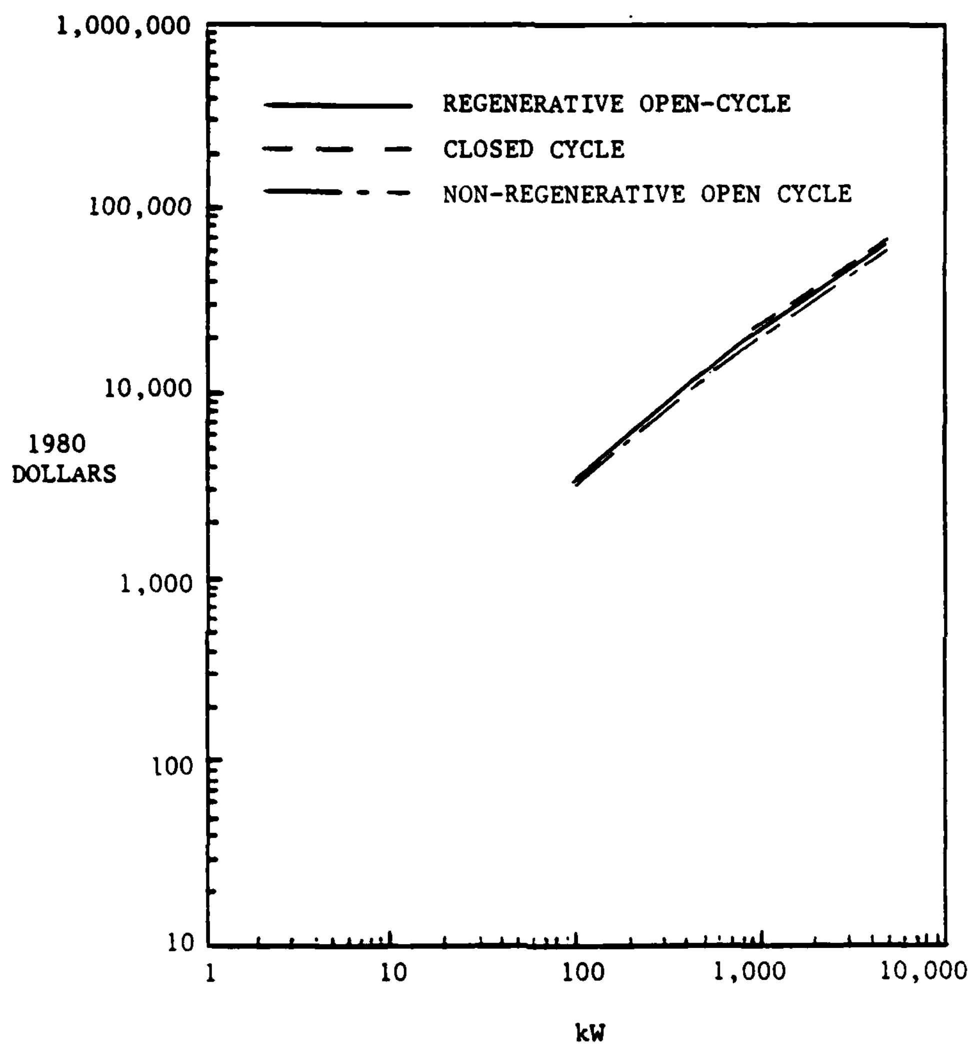

Figure 10. GAS TURBINE ANNUAL OPERATIONS AND MAINTENANCE COST

System Efficiency. Gas turbine "System Efficiency" parameter values are presented in Table 14 and in Figure 11. The efficiency of the open-cycle, regenerative system is greater than that of the nonregenerative open-cycle system because of the use of the turbine exhaust gas for combustion air preheat. Closed-cycle gas turbines have efficiency values between those of the regenerative and nonregenerative open-cycle gas turbine systems. Efficiency values for small regenerative systems (1.5 kW to 5.0 kW) are less reliable because of greater data variation in this size range.

Table 14. GAS TURBINE SYSTEM EFFICIENCY (%)

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE	CLOSED CYCLE	NON-REGENERATIVE OPEN-CYCLE
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	20.5
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	42.3	NCA	22.5
	2000	42.3	NCA	22.5
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	42.3	NCA	25.3
	2000	42.3	NCA	25.3
500.0	1980	NCA	NCA	21.1
	1985	NCA	NCA	21.1
	1990	42.3	NCA	27.4
	2000	42.3	NCA	27.4
750.0	1980	NCA	NCA	22.1
	1985	NCA	NCA	22.1
	1990	42.3	NCA	27.5
	2000	42.3	NCA	27.5
1000.0	1980	NCA	NCA	22.7
	1985	36.6	33.3	22.7
	1990	42.3	33.3	27.2
	2000	42.3	41.7	27.2
5000.0	1980	36.6	NCA	25.7
	1985	36.6	34.4	25.7
	1990	42.3	34.4	29.4
	2000	42.3	43.2	29.4

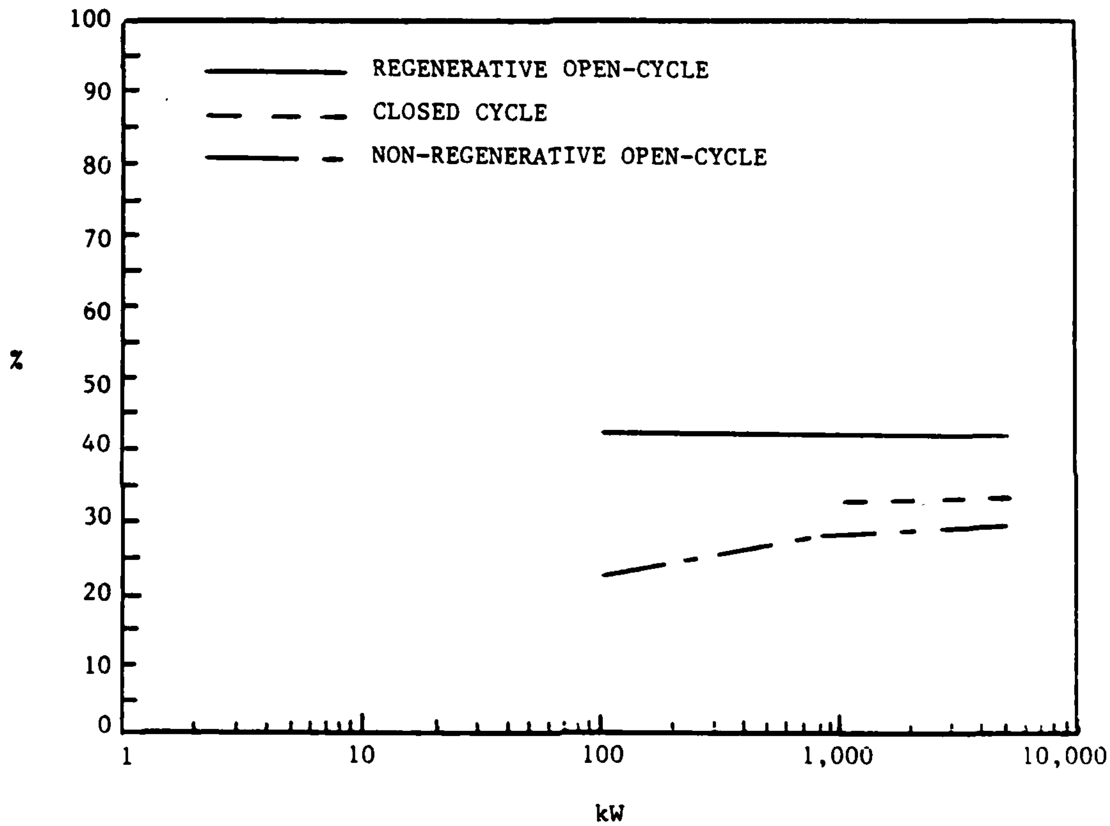

Figure 11. GAS TURBINE SYSTEM EFFICIENCY

__Fuel Consumption.__ Gas turbine "Fuel Consumption" parameter values are presented in Table 15 and in Figure 12.

Table 15. GAS TURBINE FUEL CONSUMPTION

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE Btu/hr	CLOSED CYCLE gal/hr	NON-REGENERATIVE OPEN-CYCLE Btu/hr
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	9.99E05
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	8.07E05	NCA	1.52E06
	2000	8.07E05	NCA	1.52E06
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.02E06	NCA	3.37E06
	2000	2.02E06	NCA	3.37E06
500.0	1980	NCA	NCA	8.09E06
	1985	NCA	NCA	8.09E06
	1990	4.03E06	NCA	6.23E06
	2000	4.03E06	NCA	6.23E06
750.0	1980	NCA	NCA	1.16E07
	1985	NCA	NCA	1.16E07
	1990	6.05E06	NCA	9.31E06
	2000	6.05E06	NCA	9.31E06
1000.0	1980	NCA	NCA	1.51E07
	1985	9.32E06	68.9	1.51E07
	1990	8.07E06	68.9	1.26E07
	2000	8.07E06	55.0	1.26E07
5000.0	1980	4.67E07	NCA	6.65E07
	1985	4.67E07	333	6.65E07
	1990	4.03E07	333	5.81E07
	2000	4.03E07	266	5.81E07

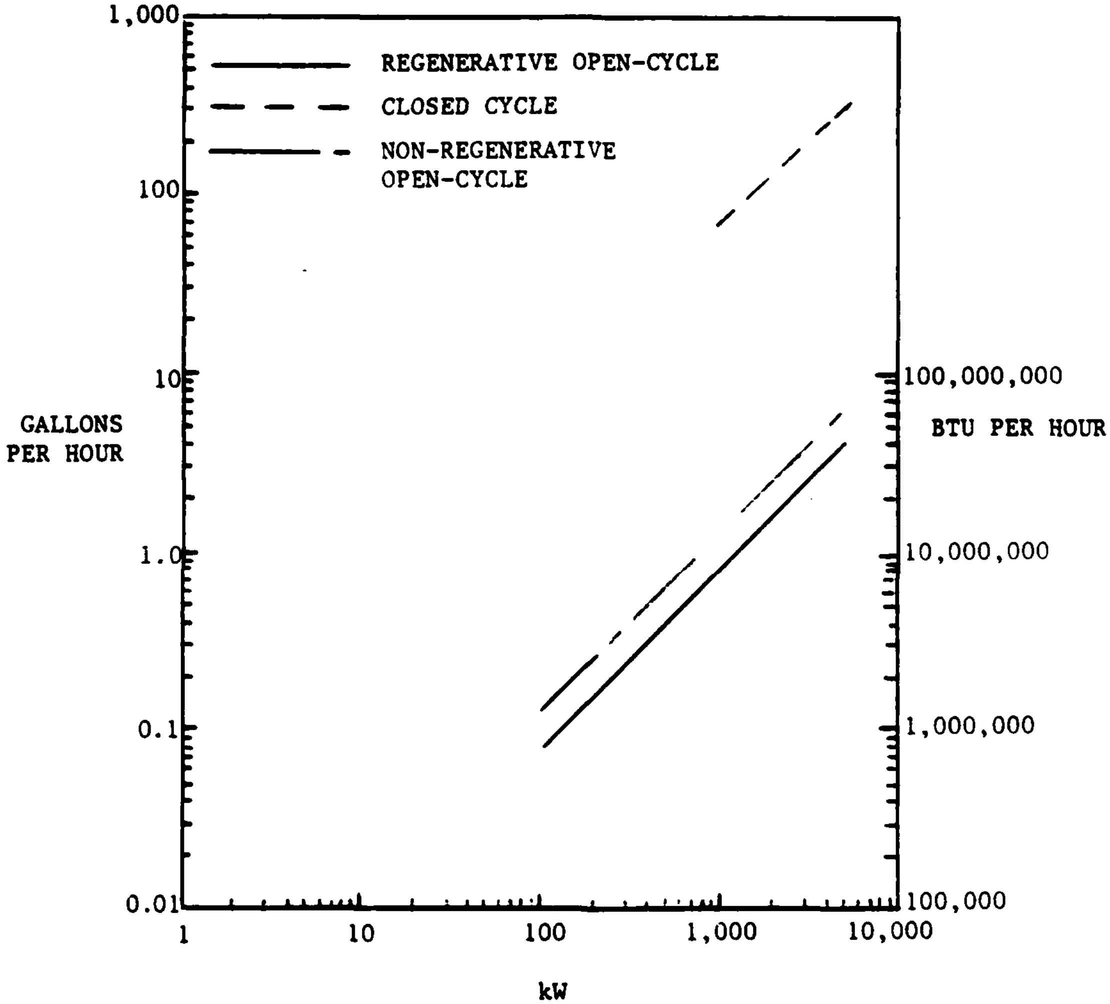

Figure 12. GAS TURBINE FUEL CONSUMPTION

Annual Fuel Cost. Gas turbine "Annual Fuel Cost" parameter values are presented in Table 16 and in Figure 13.

Table 16. GAS TURBINE ANNUAL FUEL COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE	CLOSED CYCLE	NON-REGENERATIVE OPEN-CYCLE
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	1.95E04
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.57E04	NCA	2.96E04
	2000	1.57E04	NCA	2.96E04
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.93E04	NCA	6.57E04
	2000	3.93E04	NCA	6.57E04
500.0	1980	NCA	NCA	8.29E04
	1985	NCA	NCA	1.58E05
	1990	7.85E04	NCA	1.21E05
	2000	7.85E04	NCA	1.21E05
750.0	1980	NCA	NCA	1.19E05
	1985	NCA	NCA	2.26E05
	1990	1.18E05	NCA	1.81E05
	2000	1.18E05	NCA	1.81E05
1000.0	1980	NCA	NCA	1.55E05
	1985	1.82E05	4.73E05	2.94E05
	1990	1.57E05	4.73E05	2.45E05
	2000	1.57E05	3.77E05	2.45E05
5000.0	1980	4.78E05	NCA	6.81E05
	1985	9.98E05	2.29E06	1.29E06
	1990	7.85E05	2.29E06	1.13E06
	2000	7.85E05	1.83E06	1.13E06

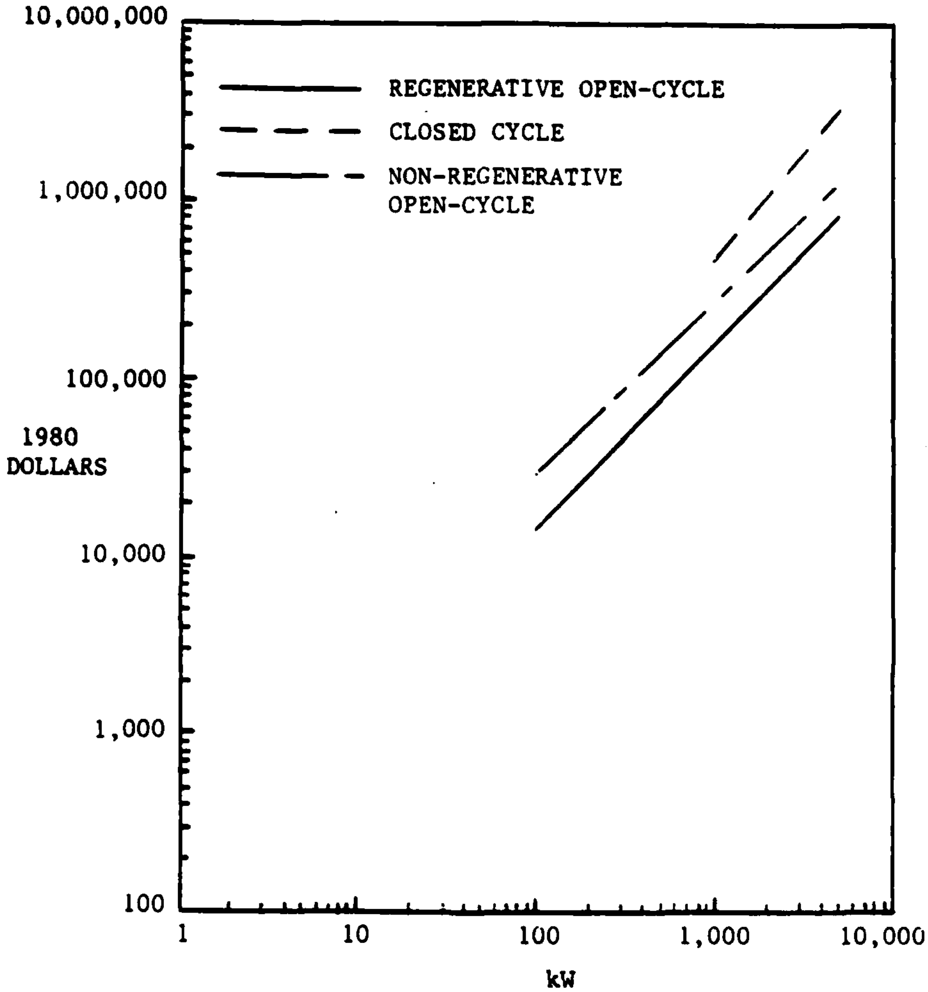

Figure 13. GAS TURBINE ANNUAL FUEL COST

__Life-Cycle Cost.__ Gas turbine "Life-Cycle Cost" parameter values are presented in Table 17 and in Figure 14.

Table 17. GAS TURBINE LIFE-CYCLE COST (1980 cents/kW)

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE	CLOSED CYCLE	NON-REGENERATIVE OPEN-CYCLE
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	2.37
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.42	NCA	2.15
	2000	1.42	NCA	2.15
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.31	NCA	1.86
	2000	1.31	NCA	1.86
500.0	1980	NCA	NCA	1.27
	1985	NCA	NCA	2.08
	1990	1.24	NCA	1.68
	2000	1.24	NCA	1.68
750.0	1980	NCA	NCA	1.20
	1985	NCA	NCA	1.97
	1990	1.21	NCA	1.64
	2000	1.21	NCA	1.64
1000.0	1980	NCA	NCA	1.15
	1985	1.32	2.90	1.90
	1990	1.18	2.90	1.64
	2000	1.18	2.38	1.64
5000.0	1980	0.74	NCA	0.95
	1985	1.21	2.71	1.61
	1990	1.07	2.71	1.44
	2000	1.07	2.21	1.44

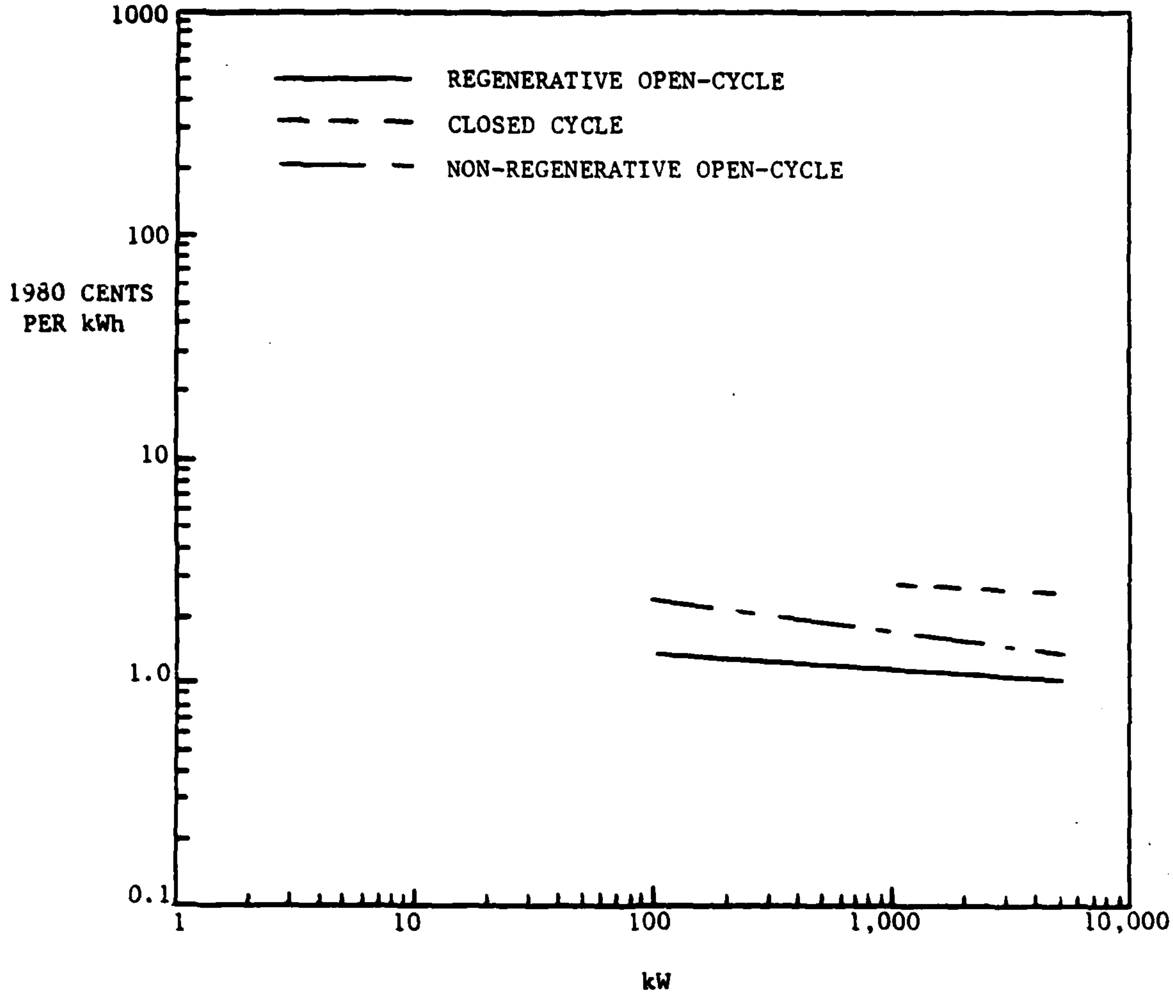

Figure 14. GAS TURBINE LIFE-CYCLE COST

System Volume. Gas turbine "System Volume" parameter values are presented in Table 18.

Table 18. GAS TURBINE SYSTEM VOLUME (CUBIC FEET)

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE	CLOSED CYCLE	NON-REGENERATIVE OPEN-CYCLE
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	3.58E01
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	4.86E01	NCA	4.5E01
	2000	4.86E01	NCA	4.5E01
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.12E02	NCA	8.45E01
	2000	1.12E02	NCA	8.45E01
500.0	1980	NCA	NCA	1.14E02
	1985	NCA	NCA	1.14E02
	1990	1.30E02	NCA	1.14E02
	2000	1.30E02	NCA	1.14E02
750.0	1980	NCA	NCA	1.42E02
	1985	NCA	NCA	1.42E02
	1990	1.65E02	NCA	1.42E02
	2000	1.65E02	NCA	1.42E02
1000.0	1980	NCA	NCA	1.46E02
	1985	1.72E02	1.89E02	1.46E02
	1990	1.72E02	1.89E02	1.46E02
	2000	1.72E02	1.89E02	1.46E02
5000.0	1980	2.08E02	NCA	1.73E02
	1985	2.08E02	2.29E02	1.73E02
	1990	2.08E02	2.29E02	1.73E02
	2000	2.08E02	2.29E02	1.73E02

System Weight. Gas turbine "System Weight" parameter values are presented in Table 19.

Table 19. GAS TURBINE SYSTEM WEIGHT (POUNDS)

POWER OUTPUT LEVEL, KW	YEAR	REGENERATIVE OPEN-CYCLE	CLOSED CYCLE	NON-REGENERATIVE OPEN-CYCLE
1.5	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
5.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
20.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
30.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	NCA
60.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	NCA	NCA	173
100.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	318	NCA	289
	2000	318	NCA	289
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	795	NCA	723
	2000	795	NCA	723
500.0	1980	NCA	NCA	1.45E03
	1985	NCA	NCA	1.45E03
	1990	1600	NCA	1.45E03
	2000	1600	NCA	1.45E03
750.0	1980	NCA	NCA	2.17E03
	1985	NCA	NCA	2.17E03
	1990	2390	NCA	2.17E03
	2000	2390	NCA	2.17E03
1000.0	1980	NCA	NCA	2.89E03
	1985	3180	3.61E03	2.89E03
	1990	3180	3.61E03	2.89E03
	2000	3180	3.61E03	2.89E03
5000.0	1980	1.60E04	NCA	1.45E04
	1985	1.60E04	1.81E04	1.45E04
	1990	1.60E04	1.81E04	1.45E04
	2000	1.60E04	1.81E04	1.45E04

Fuel Requirements and Capabilities. Regenerative open-cycle gas turbines use natural gas as their designated fuel. To the extent that they may use liquid and gaseous fuels, the regenerative open-cycle gas turbine has multi-fuel capability. Nonregenerative open-cycle gas turbines use natural gas as their designated fuel. To the extent that they may use liquid and gaseous fuels, the nonregenerative open-cycle gas turbine has multi-fuel capability. Both regenerative and nonregenerative open-cycle gas turbines have stringent fuel purity requirements. Closed-cycle gas turbines use residual fuel oil as their designated fuel; they have multi-fuel capability, including solid fuels.

Start-up Time. Gas turbine start-up time is 1 minute.

Shutdown Time. Gas turbine shutdown time is 2 minutes.

Reliability. Gas turbine "reliability" has an ordinal score of 3 indicating average reliability. Gas turbines have comparable reliability to diesels because they too have numerous moving parts and cycle thermally.

Environmental Constraints. Gas turbines have an ordinal score of 4 for "Environmental Constraints" indicating moderate potential environmental insult. Gas turbines have environmental constraints comparable to diesels. Major insults are NO_x emissions in exhaust and noise from expanding hot gases.

Location Constraints. Gas turbines have an ordinal score of 3 indicating average locational constraints. Gas turbines have location constraints comparable to diesels because of similar fuel availability, delivery, and storage requirements.

Operation Constraints. Gas turbines have an ordinal score of 4 indicating moderate turn-down capability with moderate efficiency penalty. Gas turbines have operation constraints comparable to diesels. Gas turbine efficiency is lower at part loads, and emissions are increased.

Stirlings

There are two types of Stirling engines of interest in this study: the free-piston and the kinematic. The differences in the two technologies do not affect the system configuration (Figure 15). The primary difference between the free-piston Stirling and the kinematic Stirling is that the stroke of the pistons in the kinematic design is controlled through a mechanical linkage whereas the stroke in the free-piston is controlled by the working fluid in the cylinder. Stirlings produce shaft power, which is then converted to AC power by an AC generator.

Technology Status. Free-piston Stirlings are expected to be commercially available at capacities of 1.5 and 5.0 kW in 1990. They are expected to be commercially available at a capacity of 20.0 kW in 2000. Kinematic Stirlings are expected to be commercially available up to 500.0 kW in 1990 and commercially available at capacities of 750.0 and 1000.0 kW in 2000.

The primary factors delaying the commercialization of either the kinematic or free-piston Stirling for the stationary engine market are development of an efficient and cost-effective burner/heater head combination and development of effective and reliable piston (displacer) rod seals to prevent oil penetration to hot areas and to minimize working fluid (He or H_2) losses.

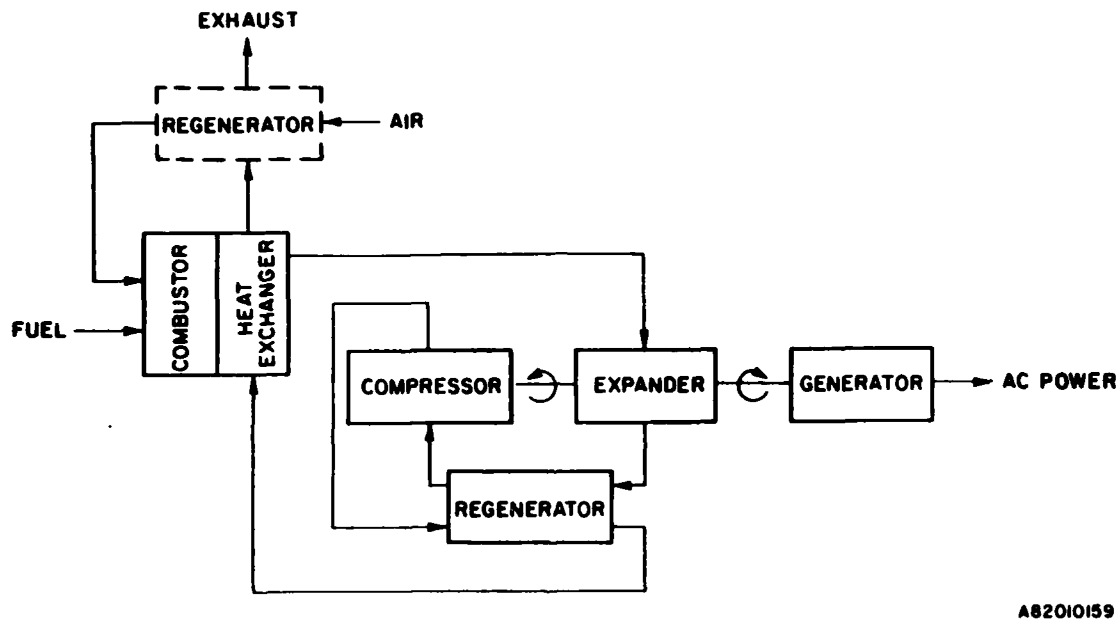

Figure 15. STIRLING SYSTEMS

Type. Stirling system "Type" parameter values are presented in Table 20. Stirling systems below 250 kW are mobile.

Table 20. STIRLING SYSTEM TYPE (Mobile, Transportable)

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON	KINEMATIC
1.5	1980	NCA	NCA
	1985	NCA	NCA
	1990	M	M
	2000	M	M
5.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	M	M
	2000	M	M
20.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	M
	2000	M	M
30.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	M
	2000	NCA	M
60.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	M
	2000	NCA	M
100.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	M
	2000	NCA	M
250.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	T
	2000	NCA	M
500.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	T
	2000	NCA	M
750.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	T
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	T
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

System Acquisition Cost. Stirling "System Acquisition Cost" parameter values are presented in Table 21 and in Figure 16. There is no differentation in free-piston and kinematic Stirling system costs becase technology development is too preliminary to identify significant cost differences. For both engine types the costs of generators, combustor/heat exchanges, and regenerators are expected to be about the same. The main difference is the mechanical linkage of the kinematic Stirling versus the free-piston's lack of a mechanical linkage.

Table 21. STIRLING SYSTEM ACQUISITION COST
(1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON	KINEMATIC	
1.5	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	1.35E03	1.35E03	
	2000	1.35E03	1.35E03	
5.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	4.50E03	4.50E03	
	2000	4.50E03	4.50E03	
20.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	1.20E04	
	2000	1.20E04	1.20E04	
30.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	1.65E04	
	2000	NCA	1.65E04	
60.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	3.00E04	
	2000	NCA	3.00E04	
100.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	5.00E04	
	2000	NCA	5.00E04	
250.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	1.25E05	
	2000	NCA	1.25E05	
500.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	2.21E05	
	2000	NCA	2.21E05	
750.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	NCA	
	2000	NCA	3.31E05	
1000.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	NCA	
	2000	NCA	4.41E05	
5000.0	1980	NCA	NCA	
	1985	NCA	NCA	
	1990	NCA	NCA	
	2000	NCA	NCA	

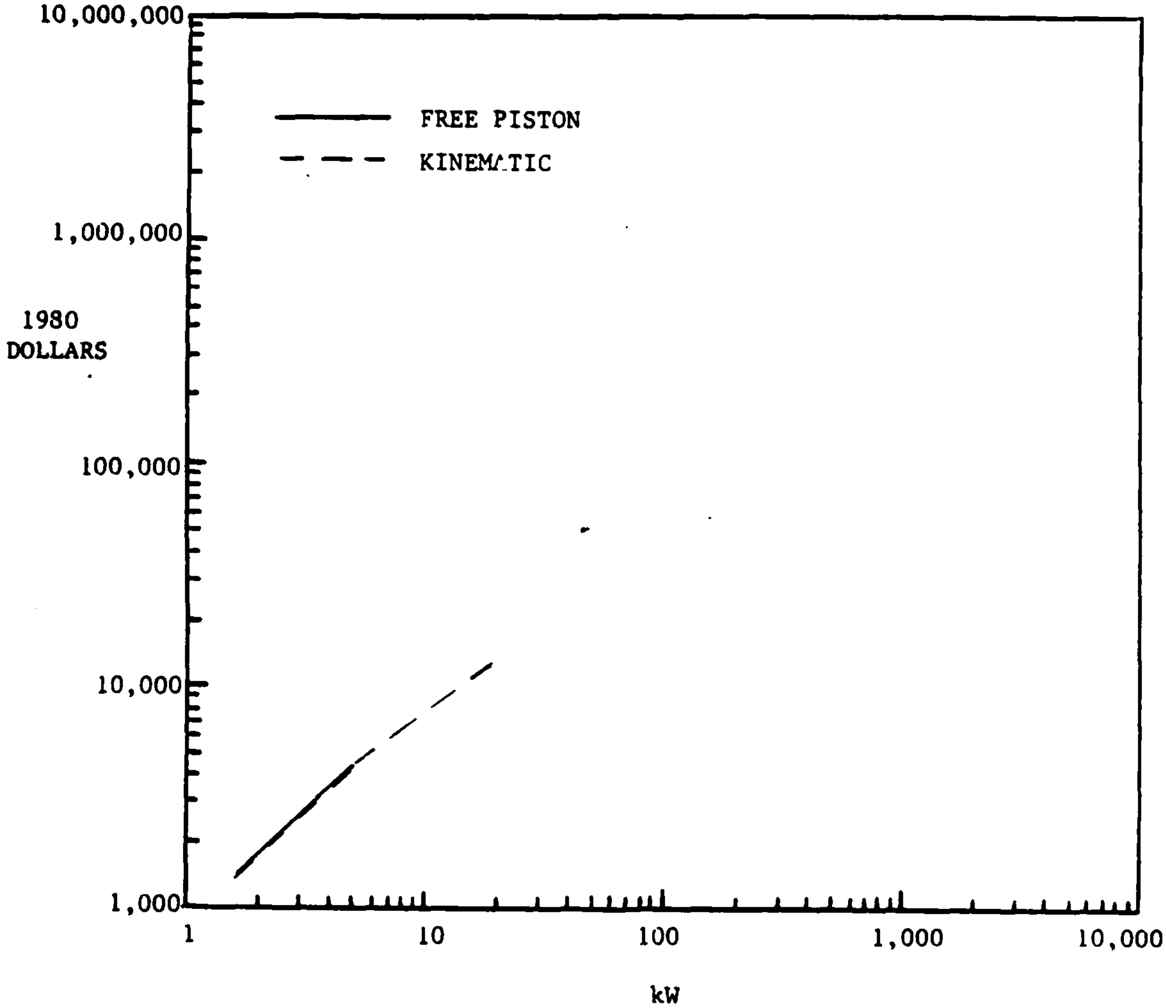

Figure 16. STIRLING SYSTEM ACQUISITION COST

Annual Operations and Maintenance Costs. Stirling "Annual Operations and Maintenance Costs" parameter values are presented in Table 22 and in Figure 17.

Table 22. STIRLING ANNUAL OPERATIONS AND MAINTENANCE COSTS (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON	KINEMATIC
1.5	1980	NCA	NCA
	1985	NCA	NCA
	1990	6.75E01	6.75E01
	2000	6.75E01	6.75E01
5.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	2.25E02	2.25E02
	2000	2.25E02	2.25E02
20.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	6.00E02
	2000	6.00E02	6.00E02
30.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	8.25E02
	2000	NCA	8.25E02
60.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.50E03
	2000	NCA	1.50E03
100.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	2.50E03
	2000	NCA	2.50E03
250.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	6.25E03
	2000	NCA	6.25E03
500.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.11E04
	2000	NCA	1.11E04
750.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	1.66E04
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	2.21E04
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

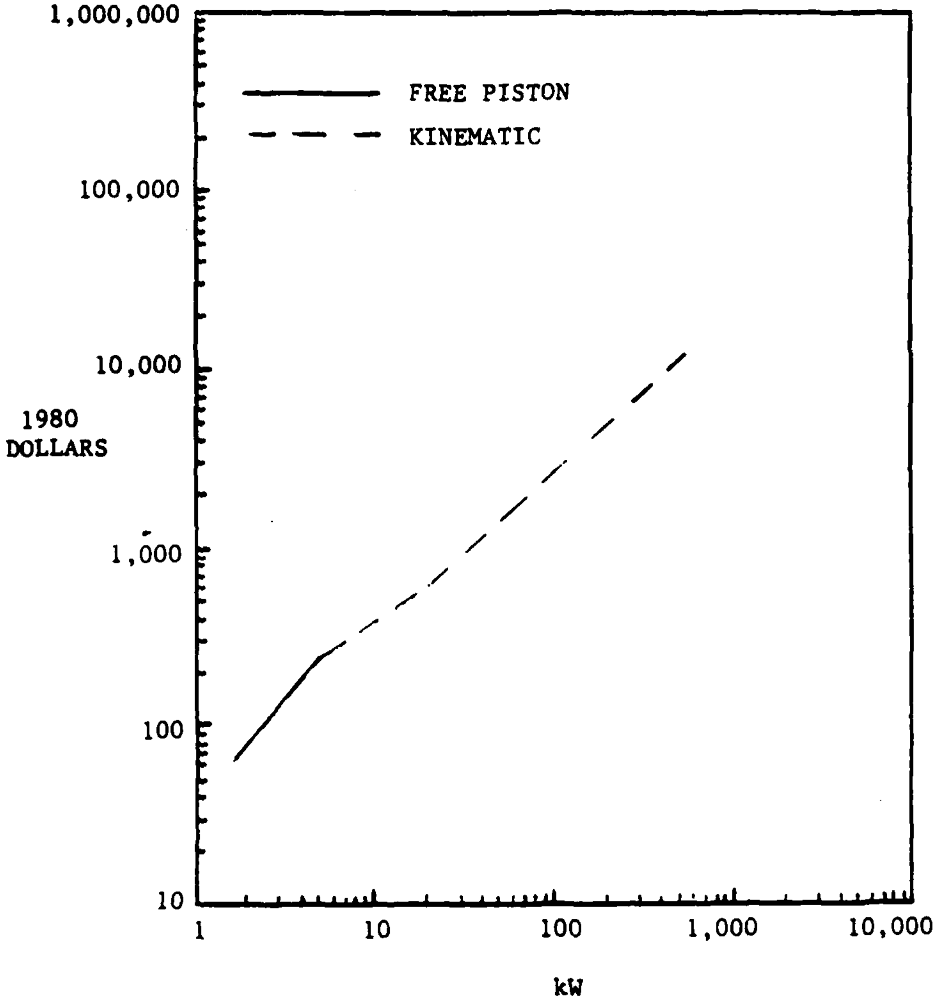

Figure 17. STIRLING ANNUAL OPERATIONS AND MAINTENANCE COST

<u>System Efficiency</u>. Stirling "System Efficiency" parameter values are presented in Table 23 and Figure 18. There is no differentiation in the efficiency of Stirling systems with size and time for several reasons. Technology development is too preliminary to identify significant efficiency differences. Efficiency differences are driven primarily by friction in bearings and heat transfer to the working fluid. Small systems have relatively high frictional losses and also have losses from clearances around power and displace pistons; however, favorable surface-to-volume relationships permit effective heat transfer and therefore high efficiency. Larger systems have relatively low frictional losses and low losses from clearances around power and displacer pistons; however, unfavorable surface-to-volume ratios do not permit effective heat transfer, thus limiting efficiency. Frictional losses and heat transfer limitations tend to cancel each other out as systems grow in size, resulting in approximately constant efficiencies versus size.

Table 23. STIRLING SYSTEM EFFICIENCY (%)

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON	KINEMATIC
1.5	1980	NCA	NCA
	1985	NCA	NCA
	1990	36.5	35.0
	2000	36.5	35.0
5.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	36.5	35.0
	2000	36.5	35.0
20.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	35.0
	2000	36.5	35.0
30.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	35.0
	2000	NCA	35.0
60.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	35.0
	2000	NCA	35.0
100.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	35.0
	2000	NCA	35.0
250.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	35.0
	2000	NCA	35.0
500.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	35.0
	2000	NCA	35.0
750.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	35.0
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	35.0
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

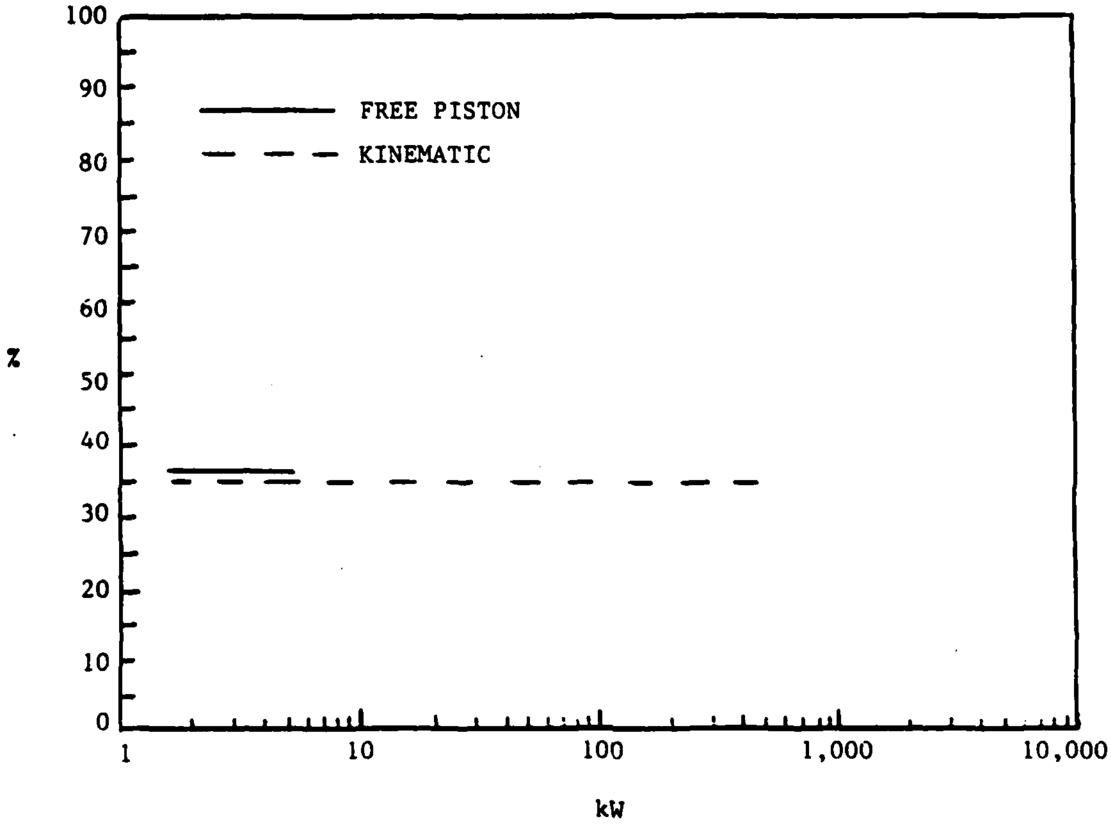

Figure 18. STIRLING SYSTEM EFFICIENCY

Fuel Consumption. Stirling "Fuel Consumption" parameter values are presented in Table 24 and in Figure 19.

Table 24. STIRLING FUEL CONSUMPTION

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON (gal/hr)	KINEMATIC (gal/hr)
1.5	1980	NCA	NCA
	1985	NCA	NCA
	1990	0.10	0.10
	2000	0.10	0.10
5.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	0.33	0.34
	2000	0.33	0.34
20.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.38
	2000	1.32	1.38
30.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	2.07
	2000	NCA	2.07
60.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	4.13
	2000	NCA	4.13
100.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	6.89
	2000	NCA	6.89
250.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	17.3
	2000	NCA	17.3
500.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	34.4
	2000	NCA	34.4
750.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	49.2
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	65.5
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

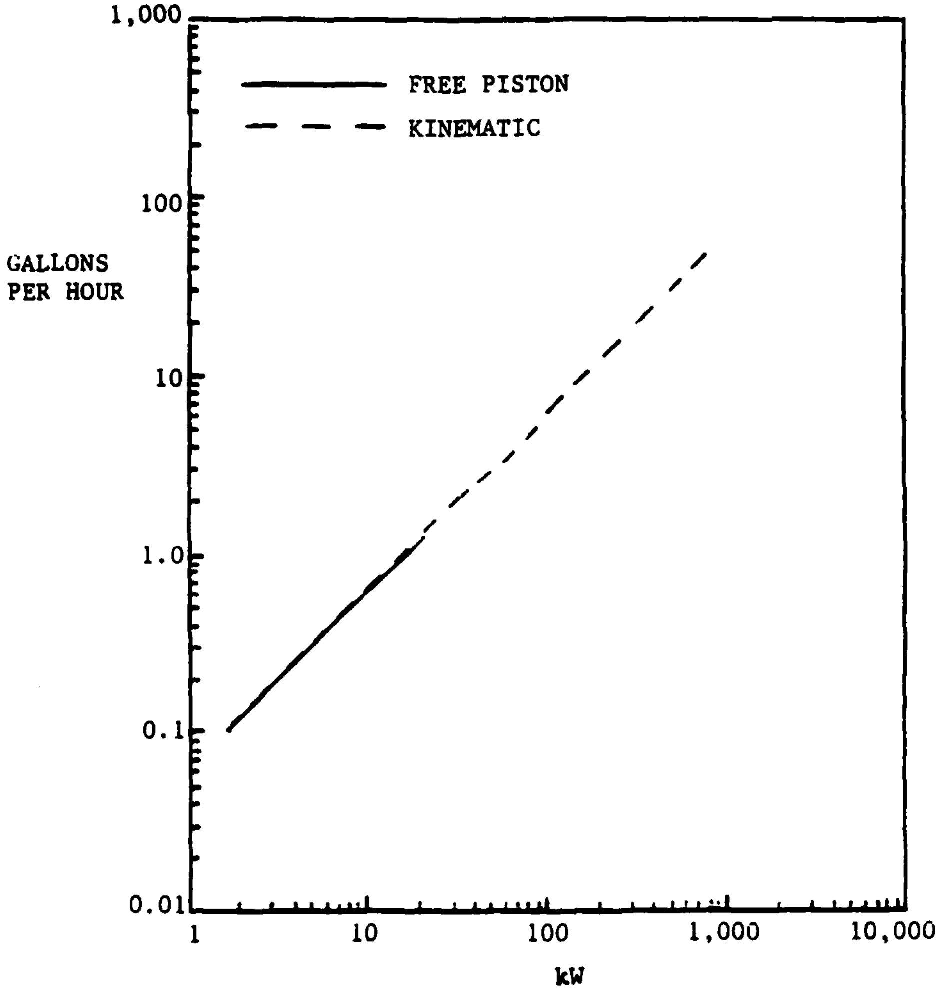

Figure 19. STIRLING FUEL CONSUMPTION

Annual Fuel Cost. Stirling "Annual Fuel Cost" parameter values (based on 1980 dollars and no real escalation) are in Table 25 and in Figure 20.

Table 25. STIRLING ANNUAL FUEL COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON	KINEMATIC
1.5	1980	NCA	NCA
	1985	NCA	NCA
	1990	9.57E02	9.91E02
	2000	9.57E02	9.91E02
5.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	3.16E03	3.31E03
	2000	3.16E03	3.31E03
20.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.33E04
	2000	1.27E04	1.33E04
30.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.99E04
	2000	NCA	1.99E04
60.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	3.97E04
	2000	NCA	3.97E04
100.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	6.63E04
	2000	NCA	6.63E04
250.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.66E05
	2000	NCA	1.66E05
500.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	3.31E05
	2000	NCA	3.31E05
750.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	3.37E05
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	4.50E05
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

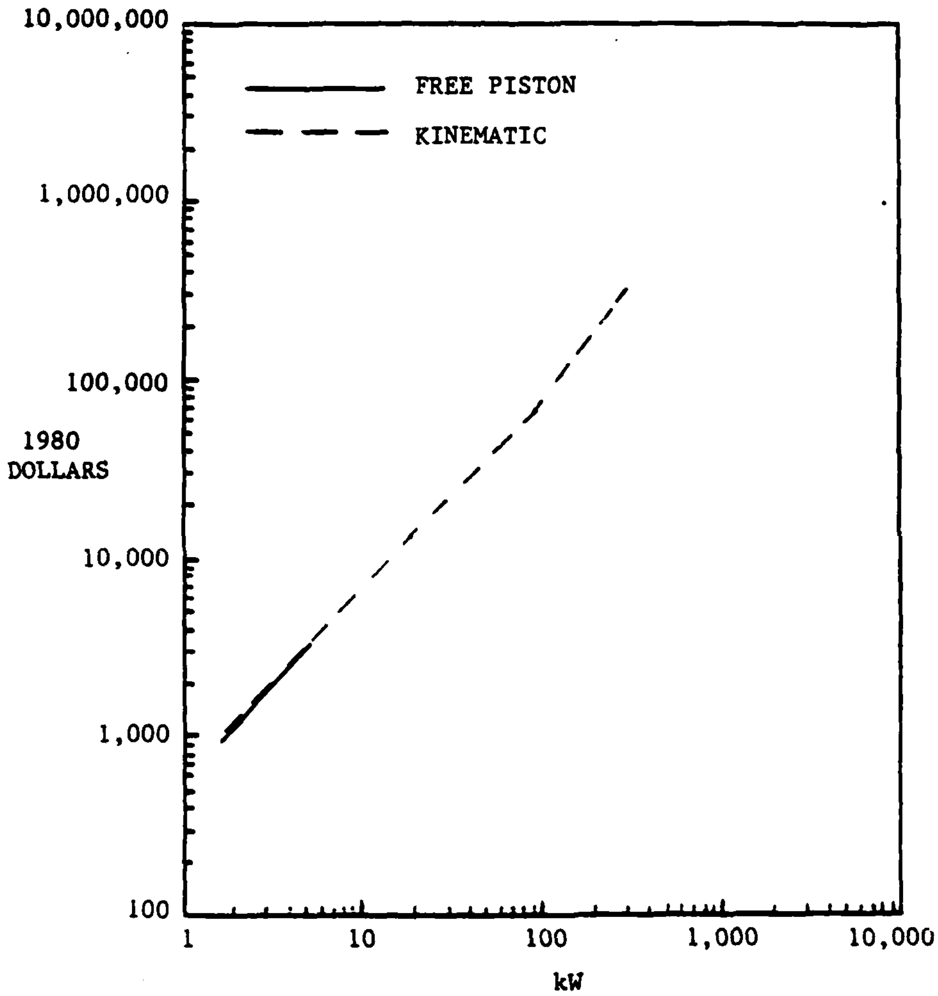

Figure 20. STIRLING ANNUAL FUEL COST

Life-Cycle Cost. Stirling "Life-Cycle Cost" parameter values are in Table 26 and in Figure 21.

Table 26. STIRLING LIFE-CYCLE COST (1980 cents/kW)

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON	KINEMATIC
1.5	1980	NCA	NCA
	1985	NCA	NCA
	1990	4.26	4.38
	2000	4.26	4.38
5.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	4.23	4.39
	2000	4.23	4.39
20.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	4.13
	2000	3.97	4.13
30.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	4.08
	2000	NCA	4.08
60.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	4.03
	2000	NCA	4.03
100.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	4.03
	2000	NCA	4.03
250.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	4.04
	2000	NCA	4.04
500.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	3.97
	2000	NCA	3.97
750.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	2.83
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	2.83
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

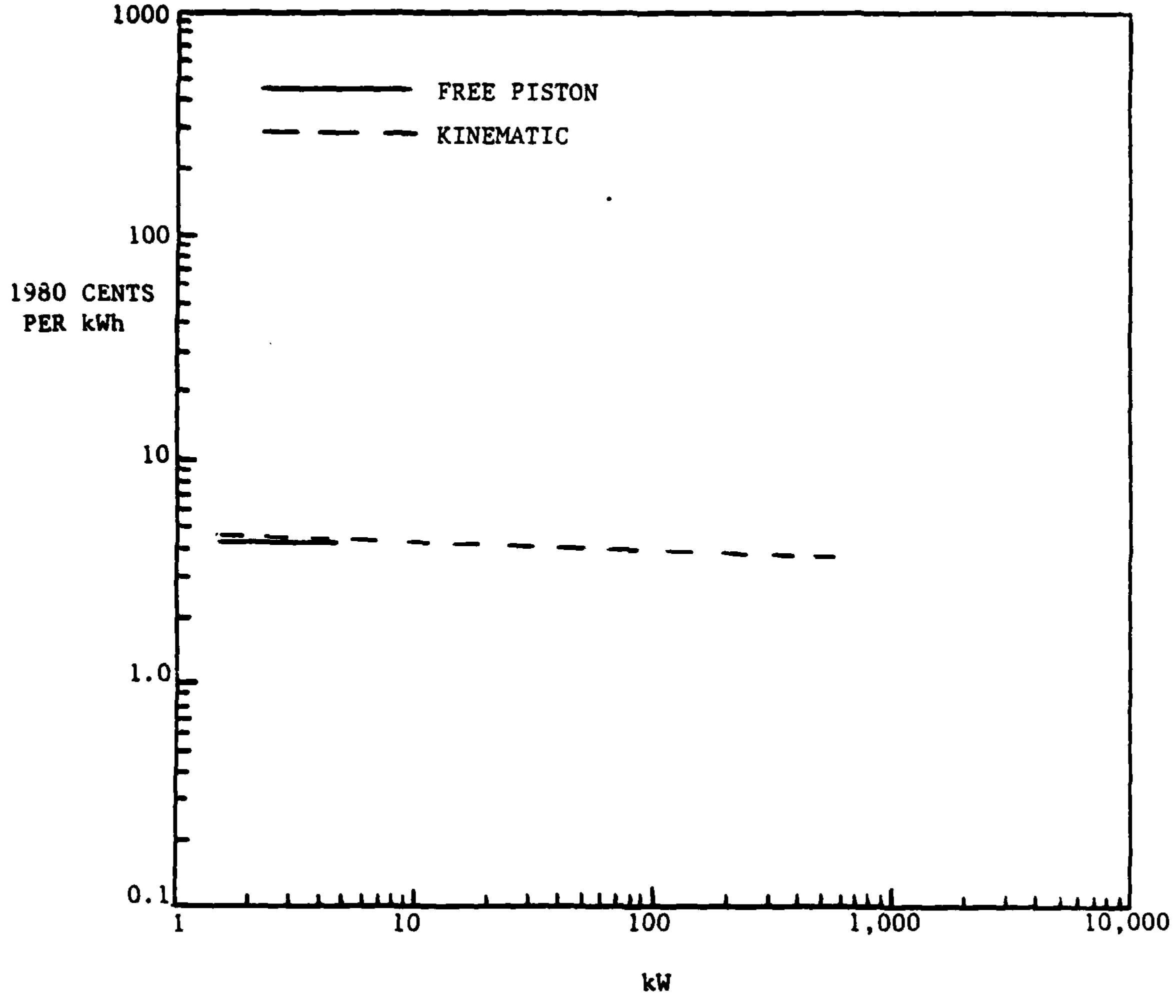

Figure 21. STIRLING LIFE-CYCLE COST

System Volume. Stirling "System Volume" parameter values are presented in Table 27. There is no differentiation in the volume of Stirling systems because the regenerator determines the dimensions of the system envelope.

Table 27. STIRLING SYSTEM VOLUME (CUBIC FEET)

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON	KINEMATIC
1.5	1980	NCA	NCA
	1985	NCA	NCA
	1990	7.05	7.05
	2000	7.05	7.05
5.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	1.71E01	1.71E01
	2000	1.71E01	1.71E01
20.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	4.42E01
	2000	4.42E01	4.42E01
30.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	5.76E01
	2000	NCA	5.76E01
60.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	8.92E01
	2000	NCA	8.92E01
100.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.22E02
	2000	NCA	1.22E02
250.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	2.10E02
	2000	NCA	2.10E02
500.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	3.22E02
	2000	NCA	3.22E02
750.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	4.26E02
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	5.29E02
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

System Weight. Stirling "System Weight" parameter values are presented in Table 28. Free-piston Stirlings systems are much lighter than kinematic Stirling systems because of mechanical simplicity.

Table 28. STIRLING SYSTEM WEIGHT (POUNDS)

POWER OUTPUT LEVEL, KW	YEAR	FREE PISTON	KINEMATIC
1.5	1980	NCA	NCA
	1985	NCA	NCA
	1990	1.08E02	2.15E02
	2000	1.08E02	2.15E02
5.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	2.96E02	5.92E02
	2000	2.96E02	5.92E02
20.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.49E03
	2000	7.45E02	1.49E03
30.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	2.07E03
	2000	NCA	2.07E03
60.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	3.59E03
	2000	NCA	3.59E03
100.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	5.42E03
	2000	NCA	5.42E03
250.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.14E04
	2000	NCA	1.14E04
500.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	2.03E04
	2000	NCA	2.03E04
750.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	2.87E04
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	3.69E04
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

Fuel Requirements and Capabilities. The designated fuel for Stirling systems is diesel. Because they are external combustion systems, Stirlings have multi-fuel capabilities. However, the capability to utilize gaseous, liquid, and solid fuels of course depends on the availability of an appropriate combustor. To date, limited work has been done on development of either gaseous or solid fuel combustors for Stirling engines.

Start-up Time. Stirling "Start-up Time" is 15 seconds.

Shutdown Time. Stirling "Shutdown Time" is 5 seconds.

Reliability. Stirling "Reliability" has an ordinal score of 4 indicating moderate reliability. Stirlings are more reliable than diesels because of fewer moving parts.

Environmental Constraints. Stirlings have an ordinal score of 5 for "Environmental Constraints," indicating minimum potential environmental insults. Stirlings have less environmental constraints than diesels because of lower levels of air emissions.

Location Constraints. Stirlings have an ordinal score of 4 indicating moderate location constraints. Stirlings have less location constraints than diesels because of potentially better fuel availability due to multifuel capability and less operational noise.

Operation Constraints. Stirlings have an ordinal score of 5 indicating excellent turn-down capability with minor efficiency penalty relative to diesels.

Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is a modification of the widely used steam cycle. However, whereas the conventional steam rankine cycle uses water as a working fluid, the organic rankine cycle uses an organic chemical as a working fluid. For operating temperatures less than 750°F, organic fluids with high molecular weight provide high cycle efficiency with less complex and costly expanders than are required when water is used as the working fluid. The ORC configuration is shown in Figure 22. ORC's produce shaft power, which is then converted to AC power by an AC generator.

Technology Status. ORC's are commercially available in all capacities.

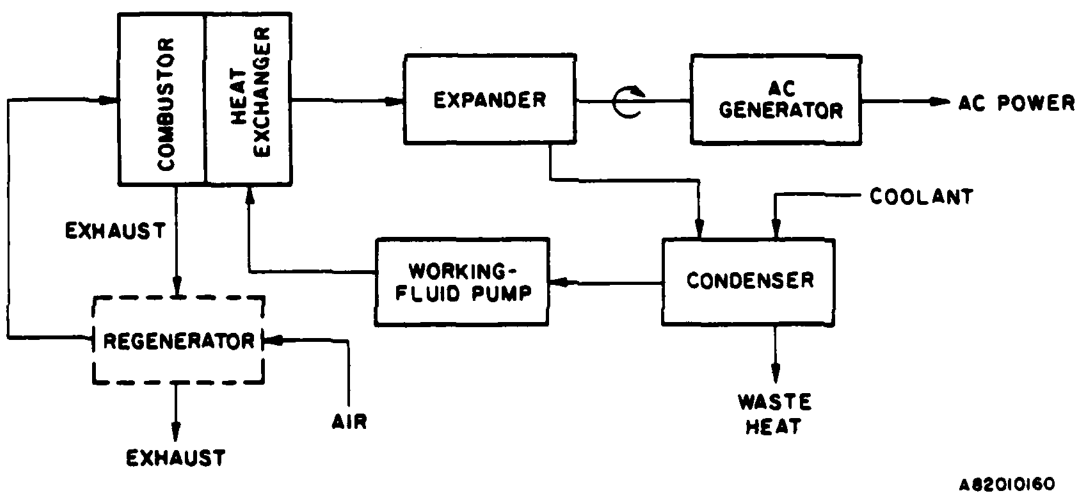

Figure 22. ORGANIC RANKINE CYCLE SYSTEMS

Type. Organic Rankine Cycle system "Type" parameter values are presented in Table 29. At capacities less than 250 kW, ORC's are mobile.

System Acquisition Cost. Organic Rankine Cycle "System Acquisition Cost" parameter values are presented in Table 30 and in Figure 23.

Table 29. ORC SYSTEM TYPE (Mobile, Transportable, Fixed)

POWER OUTPUT LEVEL, KW	YEAR			
1.5	1980		M	
	1985		M	
	1990		M	
	2000		M	
5.0	1980		M	
	1985		M	
	1990		M	
	2000		M	
20.0	1980		M	
	1985		M	
	1990		M	
	2000		M	
30.0	1980		M	
	1985		M	
	1990		M	
	2000		M	
60.0	1980		M	
	1985		M	
	1990		M	
	2000		M	
100.0	1980		M	
	1985		M	
	1990		M	
	2000		M	
250.0	1980		T	
	1985		T	
	1990		M	
	2000		M	
500.0	1980		T	
	1985		T	
	1990		T	
	2000		M	
750.0	1980		T	
	1985		T	
	1990		T	
	2000		T	
1000.0	1980		T	
	1985		T	
	1990		T	
	2000		T	
5000.0	1980		F	
	1985		T	
	1990		T	
	2000		T	

Table 30. ORC SYSTEM ACQUISITION COST (1980 dollars)

POWER OUTPUT LEVEL, KW	YEAR			
1.5	1980		1.76E03	
	1985		1.76E03	
	1990		1.76E03	
	2000		1.76E03	
5.0	1980		4.40E03	
	1985		4.40E03	
	1990		4.40E03	
	2000		4.40E03	
20.0	1980		1.27E04	
	1985		1.27E04	
	1990		1.27E04	
	2000		1.27E04	
30.0	1980		1.74E04	
	1985		1.74E04	
	1990		1.74E04	
	2000		1.74E04	
60.0	1980		3.03E04	
	1985		3.03E04	
	1990		3.03E04	
	2000		3.03E04	
100.0	1980		4.65E04	
	1985		4.65E04	
	1990		4.65E04	
	2000		4.65E04	
250.0	1980		1.07E05	
	1985		1.07E05	
	1990		1.07E05	
	2000		1.07E05	
500.0	1980		2.13E05	
	1985		2.13E05	
	1990		2.13E05	
	2000		2.13E05	
750.0	1980		3.27E05	
	1985		3.27E05	
	1990		3.27E05	
	2000		3.27E05	
1000.0	1980		4.49E05	
	1985		4.49E05	
	1990		4.49E05	
	2000		4.49E05	
5000.0	1980		2.97E06	
	1985		2.97E06	
	1990		2.97E06	
	2000		2.97E06	

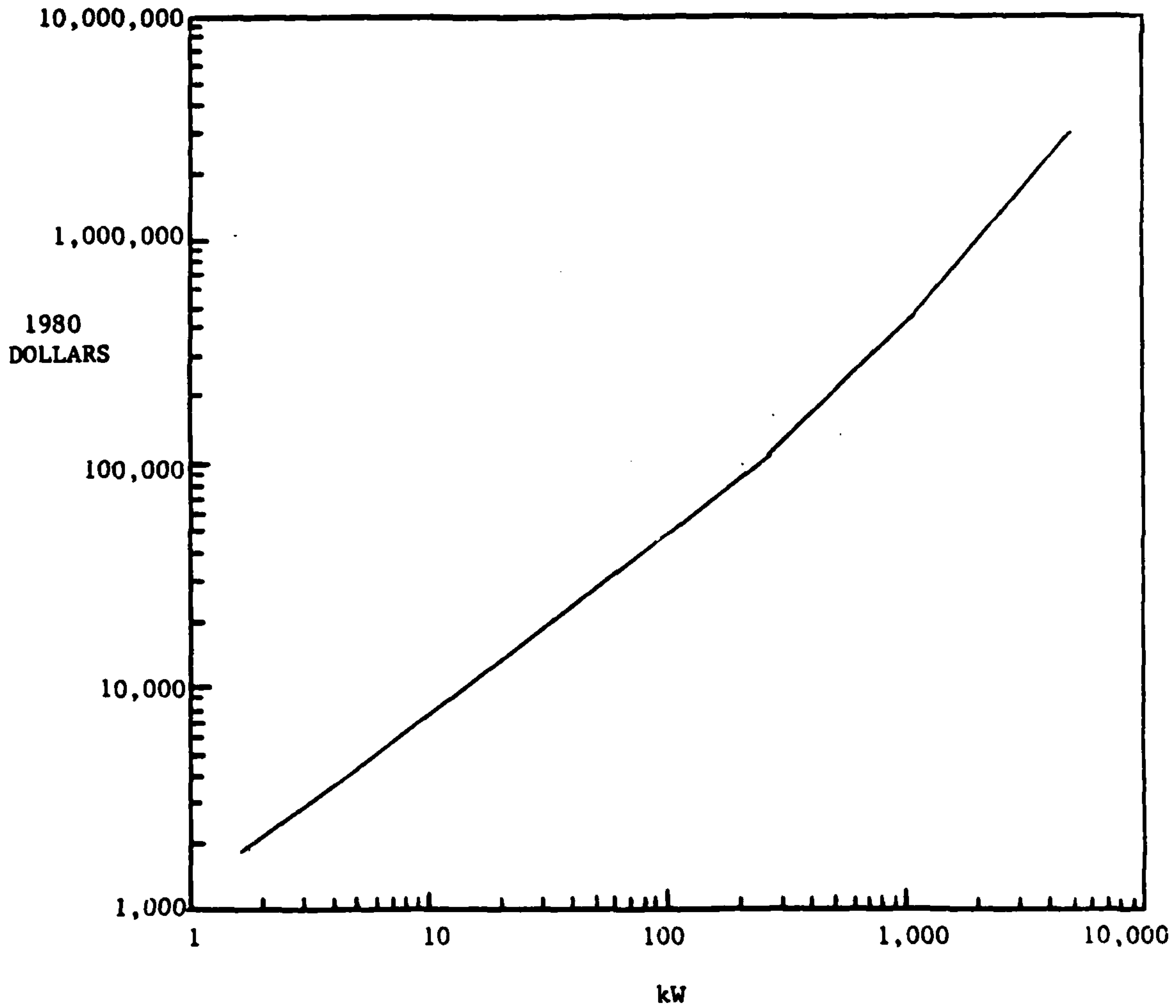

Figure 23. ORC SYSTEM ACQUISITION COST

Annual Operations and Maintenance Costs. ORC "Annual Operations and Maintenance Costs" parameter values are presented in Table 31 and in Figure 24.

Table 31. ORGANIC RANKINE CYCLE ANNUAL OPERATIONS AND MAINTENANCE COSTS (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR			
1.5	1980		2.94E02	
	1985		2.94E02	
	1990		2.94E02	
	2000		2.94E02	
5.0	1980		1.10E03	
	1985		1.10E03	
	1990		1.10E03	
	2000		1.10E03	
20.0	1980		1.27E03	
	1985		1.27E03	
	1990		1.27E03	
	2000		1.27E03	
30.0	1980		1.74E03	
	1985		1.74E03	
	1990		1.74E03	
	2000		1.74E03	
60.0	1980		3.03 E03	
	1985		3.03E03	
	1990		3.03E03	
	2000		3.03E03	
100.0	1980		4.65E03	
	1985		4.65E03	
	1990		4.65E03	
	2000		4.65E02	
250.0	1980		1.07E04	
	1985		1.07E04	
	1990		1.07E04	
	2000		1.07E04	
500.0	1980		2.13E04	
	1985		2.13E04	
	1990		2.13E04	
	2000		2.13E04	
750.0	1980		3.27E04	
	1985		3.27E04	
	1990		3.27E04	
	2000		3.27E04	
1000.0	1980		4.49E04	
	1985		4.49E04	
	1990		4.49E04	
	2000		4.49E04	
5000.0	1980		2.97E05	
	1985		2.97E05	
	1990		2.97E05	
	2000		2.97E05	

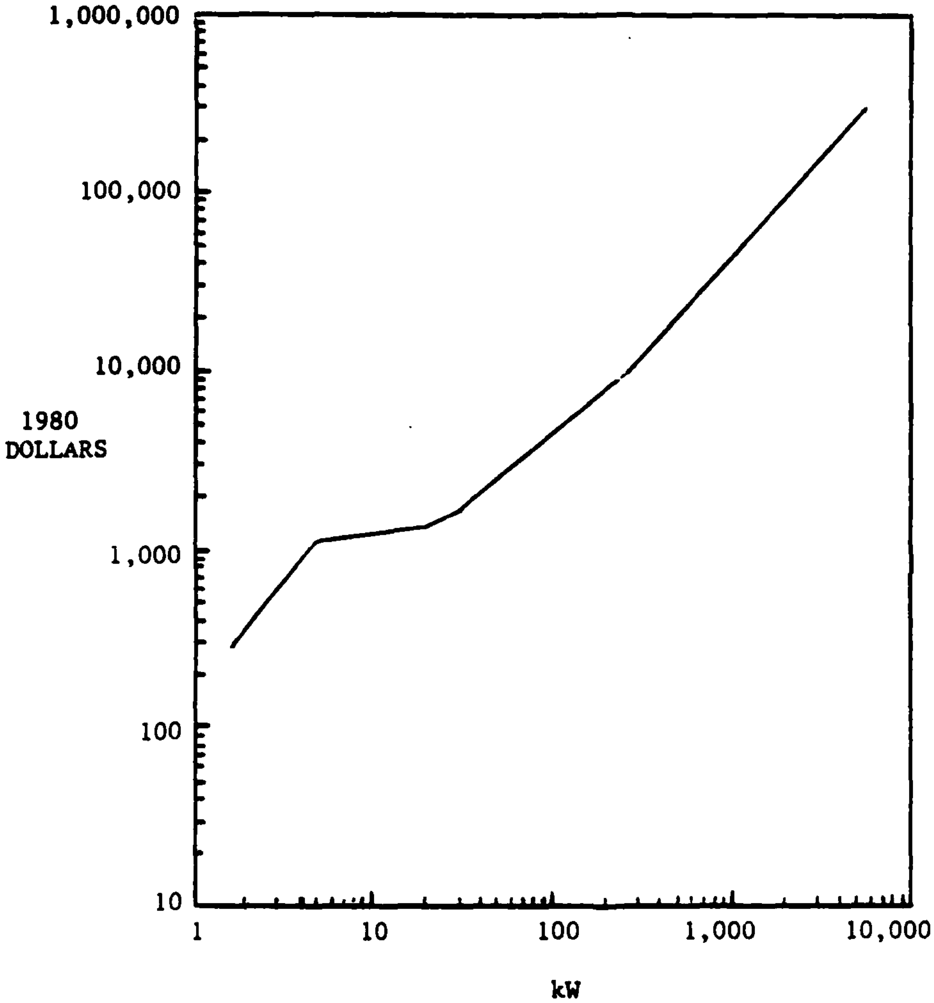

Figure 24. ORC ANNUAL OPERATIONS
AND MAINTENANCE COSTS

System Efficiency. ORC "System Efficiency" parameter values are presented in Table 32 and in Figure 25. Efficiency value of the 1.5 kW size should be used with caution because it is of the same magnitude as the standard deviation.

Table 32. ORGANIC RANKINE CYCLE SYSTEM EFFICIENCY (%)

POWER OUTPUT LEVEL, KW	YEAR			
1.5	1980		1.46	
	1985		1.58	
	1990		1.69	
	2000		1.69	
5.0	1980		5.79	
	1985		6.25	
	1990		6.69	
	2000		6.69	
20.0	1980		10.78	
	1985		11.75	
	1990		12.58	
	2000		12.58	
30.0	1980		12.24	
	1985		13.34	
	1990		14.27	
	2000		14.27	
60.0	1980		14.73	
	1985		16.20	
	1990		17.17	
	2000		17.17	
100.0	1980		1.66E01	
	1985		1.83E01	
	1990		1.94E01	
	2000		1.94E01	
250.0	1980		1.99E01	
	1985		2.18E01	
	1990		2.31E01	
	2000		2.31E01	
500.0	1980		2.24E01	
	1985		2.49E01	
	1990		2.64E01	
	2000		2.64E01	
750.0	1980		2.38E01	
	1985		2.67E01	
	1990		2.83E01	
	2000		2.83E01	
1000.0	1980		2.49E01	
	1985		2.79E01	
	1990		2.93E01	
	2000		2.93E01	
5000.0	1980		3.06E01	
	1985		3.46E01	
	1990		3.63E01	
	2000		3.63E01	

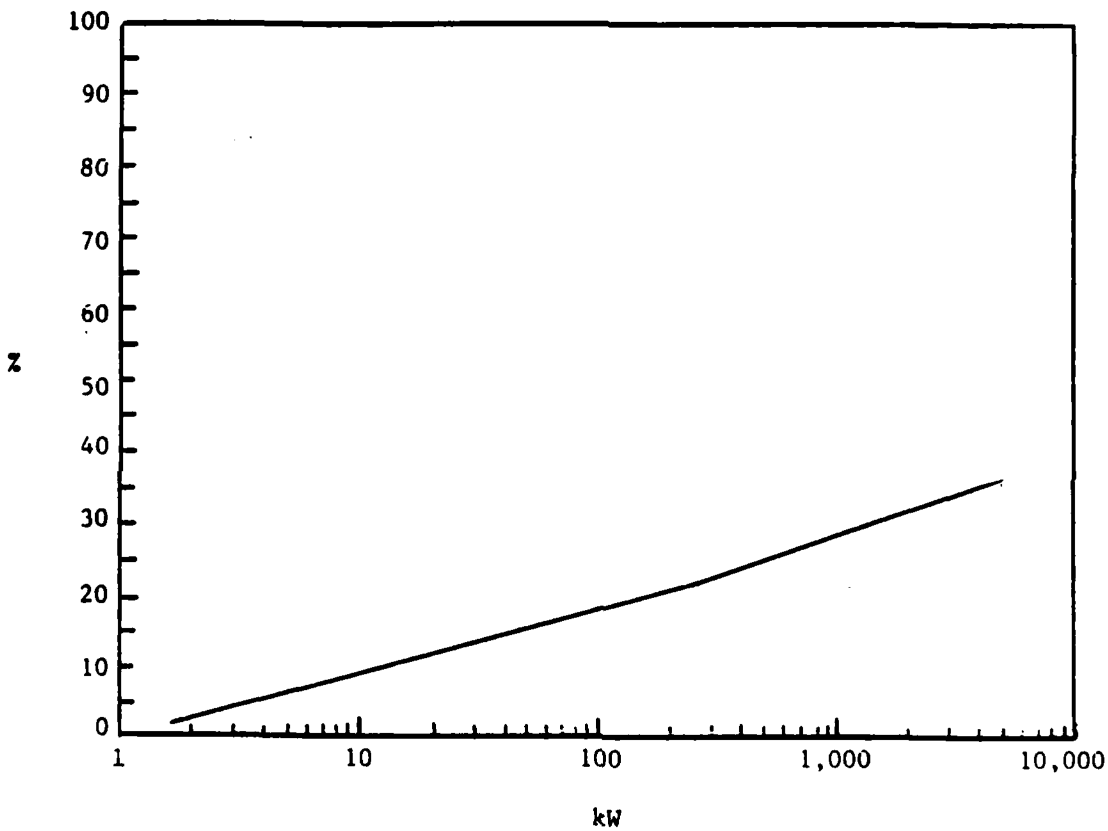

Figure 25. ORC SYSTEM EFFICIENCY

Fuel Consumption. ORC "Fuel Consumption" parameter values are presented in Table 33 and in Figure 26.

Table 33. ORGANIC RANKINE CYCLE FUEL CONSUMPTION

POWER OUTPUT LEVEL, KW	YEAR		gal/hr	
1.5	1980		2.47	
	1985		2.29	
	1990		2.14	
	2000		2.14	
5.0	1980		2.08	
	1985		1.92	
	1990		1.80	
	2000		1.80	
20.0	1980		4.47	
	1985		4.11	
	1990		3.84	
	2000		3.84	
30.0	1980		5.91	
	1985		5.43	
	1990		5.07	
	2000		5.07	
60.0	1980		9.86	
	1985		8.93	
	1990		8.42	
	2000		8.42	
100.0	1980		14.4	
	1985		13.2	
	1990		12.5	
	2000		12.5	
250.0	1980		30.3	
	1985		27.7	
	1990		26.1	
	2000		26.1	
500.0	1980		53.9	
	1985		48.3	
	1990		45.7	
	2000		45.7	
750.0	1980		72.3	
	1985		64.4	
	1990		60.8	
	2000		60.8	
1000.0	1980		92.1	
	1985		82.2	
	1990		78.2	
	2000		78.2	
5000.0	1980		375	
	1985		332	
	1990		316	
	2000		316	

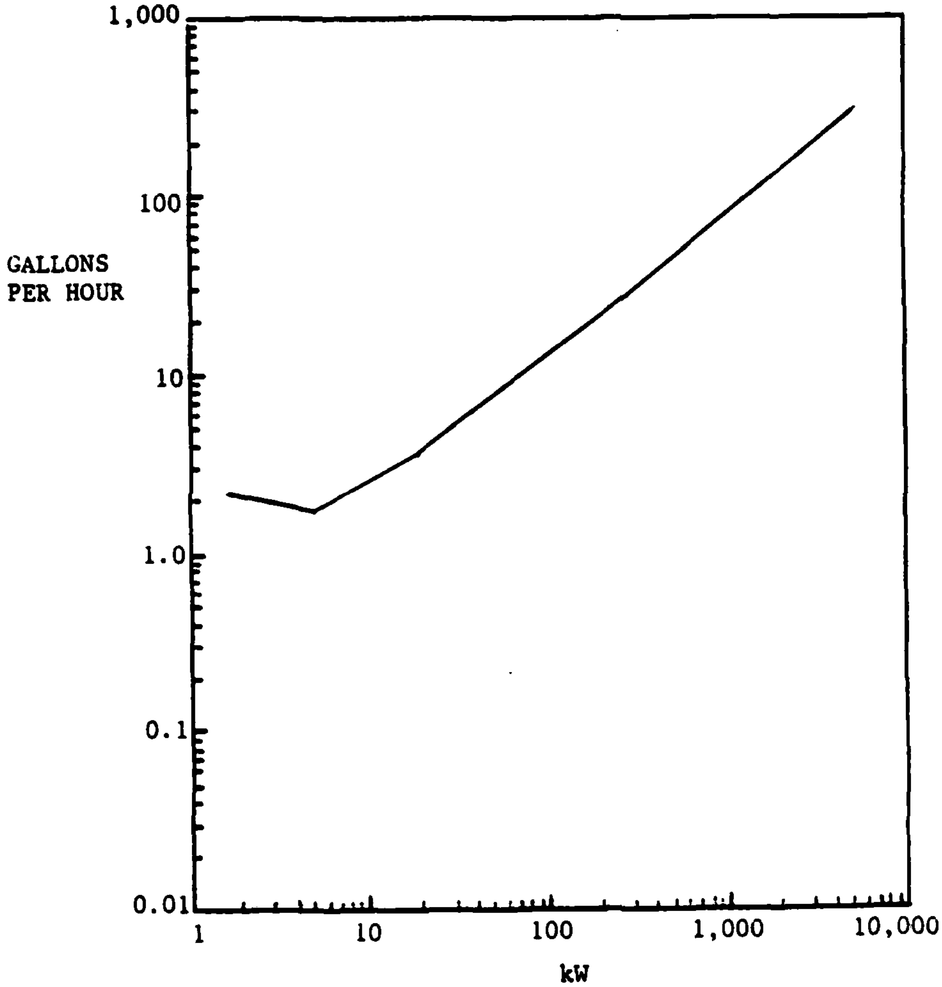

Figure 26. ORC FUEL CONSUMPTION

Annual Fuel Cost. ORC "Annual Fuel Cost" parameter values are presented in Table 34 and in Figure 27.

Table 34. ORGANIC RANKINE CYCLE ANNUAL FUEL COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR			
1.5	1980		2.32E04	
	1985		2.20E04	
	1990		2.06E04	
	2000		2.06E04	
5.0	1980		1.95E04	
	1985		1.85E04	
	1990		1.73E04	
	2000		1.73E04	
20.0	1980		4.19E04	
	1985		3.95E04	
	1990		3.69E04	
	2000		3.69E04	
30.0	1980		5.54E04	
	1985		5.22E04	
	1990		4.88E04	
	2000		4.88E04	
60.0	1980		9.24E04	
	1985		8.59E04	
	1990		8.10E04	
	2000		8.10E04	
100.0	1980		1.36E05	
	1985		1.27E05	
	1990		1.20E05	
	2000		1.20E05	
250.0	1980		2.84E05	
	1985		2.66E05	
	1990		2.51E05	
	2000		2.51E05	
500.0	1980		5.05E05	
	1985		4.65E05	
	1990		4.40E05	
	2000		4.40E05	
750.0	1980		4.92E05	
	1985		4.42E05	
	1990		4.17E05	
	2000		4.17E05	
1000.0	1980		6.26E05	
	1985		5.64E05	
	1990		5.37E05	
	2000		5.37E05	
5000.0	1980		2.55E06	
	1985		2.28E06	
	1990		2.17E06	
	2000		2.17E06	

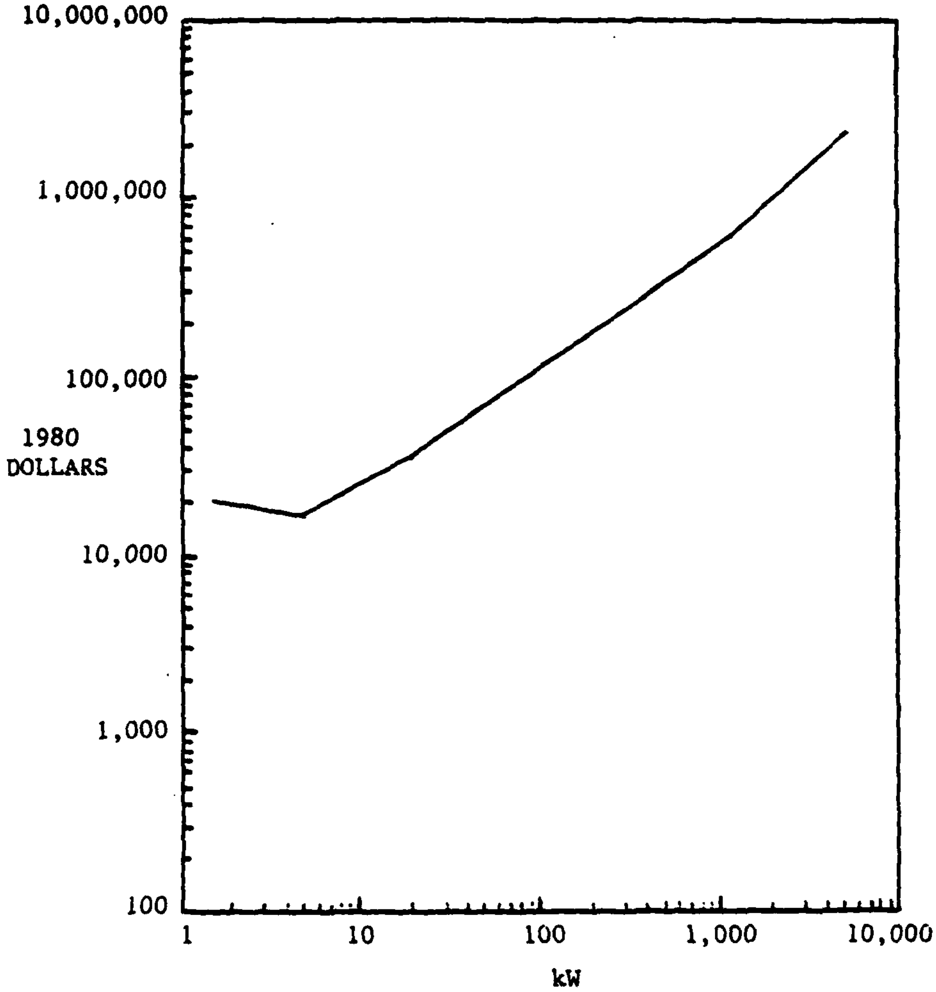

Figure 27. ORC ANNUAL FUEL COST

Life-Cycle Cost. ORC "Life-Cycle Cost" parameter values (based no 1980 dollars and no real escalation) are presented in Table 35 and in Figure 28.

Table 35. ORGANIC RANKINE CYCLE LIFE CYCLE COST (1980 cents/kW)

POWER OUTPUT LEVEL, KW	YEAR			
1.5	1980		85.3	
	1985		81.0	
	1990		75.9	
	2000		75.9	
5.0	1980		22.8	
	1985		21.7	
	1990		20.4	
	2000		20.4	
20.0	1980		12.1	
	1985		11.4	
	1990		10.7	
	2000		10.7	
30.0	1980		10.7	
	1985		10.1	
	1990		9.46	
	2000		9.46	
60.0	1980		8.91	
	1985		8.32	
	1990		7.88	
	2000		7.88	
100.0	1980		7.89	
	1985		7.40	
	1990		7.02	
	2000		7.02	
250.0	1980		6.64	
	1985		6.25	
	1990		5.92	
	2000		5.92	
500.0	1980		5.95	
	1985		5.52	
	1990		5.25	
	2000		5.25	
750.0	1980		4.05	
	1985		3.69	
	1990		3.51	
	2000		3.51	
1000.0	1980		3.91	
	1985		3.57	
	1990		3.43	
	2000		3.43	
5000.0	1980		3.45	
	1985		3.16	
	1990		3.04	
	2000		3.04	

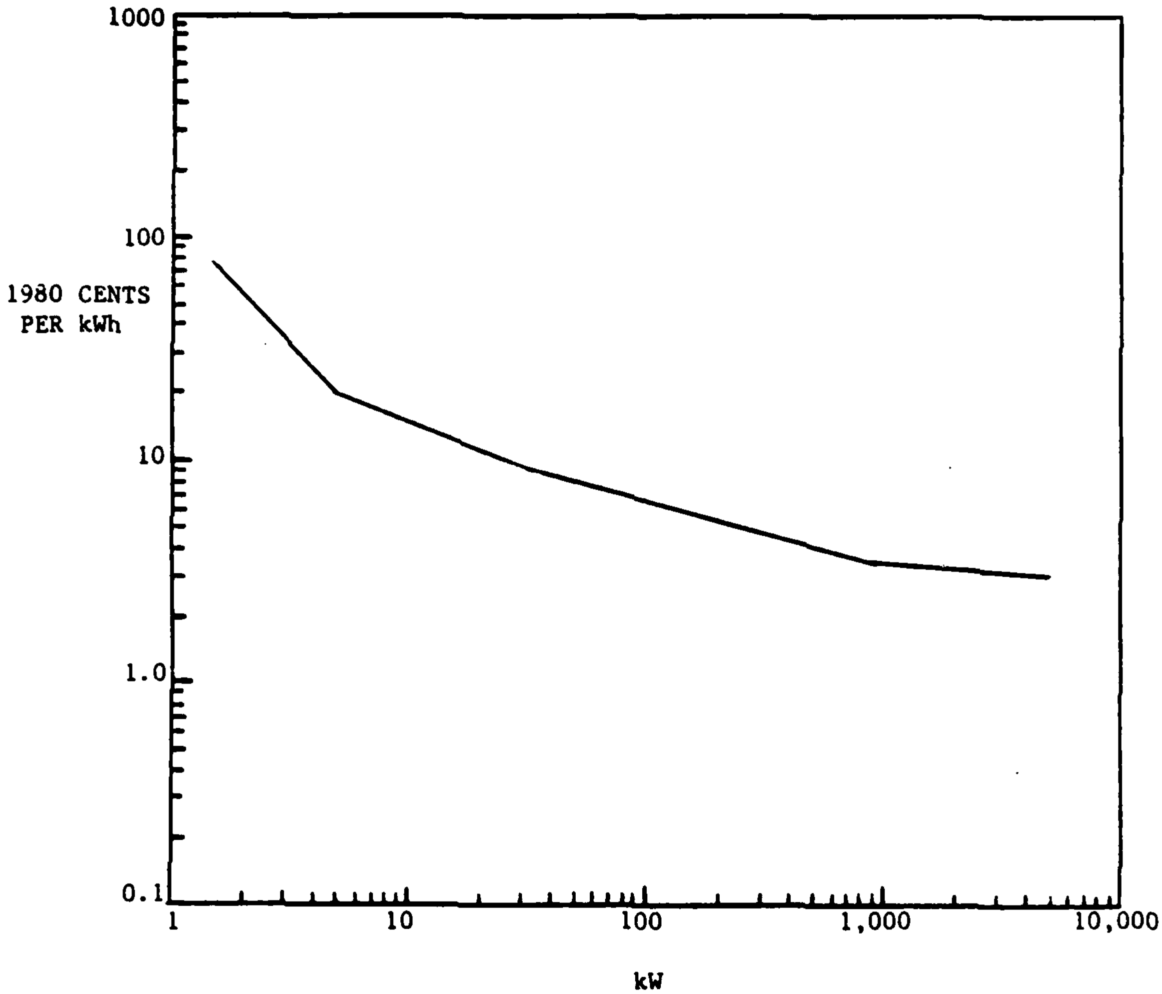

Figure 28. ORC LIFE-CYCLE COST

System Volume. ORC "System Volume" parameter values are presented in Table 36. ORC's are large-volume systems because of heat exchanger size.

Table 36. ORGANIC RANKINE CYCLE SYSTEM VOLUME (CUBIC FEET)

POWER OUTPUT LEVEL, KW	YEAR			
1.5	1980		144	
	1985		144	
	1990		144	
	2000		144	
5.0	1980		144	
	1985		144	
	1990		144	
	2000		144	
20.0	1980		144	
	1985		144	
	1990		144	
	2000		144	
30.0	1980		192	
	1985		192	
	1990		192	
	2000		192	
60.0	1980		400	
	1985		400	
	1990		400	
	2000		400	
100.0	1980		720	
	1985		720	
	1990		720	
	2000		720	
250.0	1980		1408	
	1985		1408	
	1990		1408	
	2000		1408	
500.0	1980		2880	
	1985		2880	
	1990		2880	
	2000		2880	
750.0	1980		2880	
	1985		2880	
	1990		2880	
	2000		2880	
1000.0	1980		2880	
	1985		2880	
	1990		2880	
	2000		2880	
5000.0	1980		5760	
	1985		5760	
	1990		5760	
	2000		5760	

System Weight. ORC "System Weight" parameter values are presented in Table 37.

Table 37. ORGANIC RANKINE CYCLE SYSTEM WEIGHT (POUNDS)

POWER OUTPUT LEVEL, KW	YEAR			
1.5	1980		3300	
	1985		3300	
	1990		3300	
	2000		3300	
5.0	1980		5720	
	1985		5720	
	1990		5720	
	2000		5720	
20.0	1980		4200	
	1985		4200	
	1990		4200	
	2000		4200	
30.0	1980		5400	
	1985		5400	
	1990		5400	
	2000		5400	
60.0	1980		12E03	
	1985		12E03	
	1990		12E03	
	2000		12E03	
100.0	1980		44E03	
	1985		44E03	
	1990		44E03	
	2000		44E03	
250.0	1980		44E03	
	1985		44E03	
	1990		44E03	
	2000		44E03	
500.0	1980		60.5E03	
	1985		60.5E03	
	1990		60.5E03	
	2000		60.5E03	
750.0	1980		77E03	
	1985		77E03	
	1990		77E03	
	2000		77E03	
1000.0	1980		132E03	
	1985		132E03	
	1990		132E03	
	2000		132E03	
5000.0	1980		500E03	
	1985		500E03	
	1990		500E03	
	2000		500E03	

__Fuel Requirements and Capabilities__. ORC systems have multi-fuel capabilities. For system capacities less than 750.0 kW the designated fuel is "Diesel." For system capacities greater or equal to 750.0 kW the designated fuel is "Resid." Because ORC's are external combustion systems, they may also use fuel sources such as solar thermal or waste heat. The cost and efficiency of the ORC system can vary greatly depending on the heat source (which affects the heat exchanger requirements) and the quality and quantity of the heat (which affects the operating temperature of the cycle). To the extent that thermal energy is available at less than the cost of the designated fuel for specific ORC applications, the life-cycle costs could be lower than those estimated in this study. The trade-off becomes one of capital cost versus fuel cost.

__Start-up Time__. ORC "Start-up Time" is 30 minutes.

__Shutdown Time__. ORC "Shutdown Time" is 30 minutes.

__Reliability__. ORC "Reliability" has an ordinal score of 2 indicating moderate potential unreliability. ORC's are somewhat less reliable than diesels because of numerous moving parts and temperature swings in the heat recovery system (thermal cycling).

__Environmental Constraints__. ORC have an ordinal score of 4 for "Environmental Constraints" indicating moderate potential environmental insults. This is comparable to diesels.

__Location Constraints__. ORC's have an ordinal score of 5 indicating minimum locational constraints. ORC's have significantly less locational constraints than diesels because of potentially better fuel availability and lesser manning requirements.

__Operation Constraints__. ORC's have an ordinal score of 2 indicating poor turn-down capability with large efficiency penalty. Diesels have better operational constraints. ORC's have reduced efficiencies at part load, and back-up heat sinks are required for heat recovery.

Fuel Cells

There are three types of fuel cells of interest in this study: the solid polymer electrolyte (SPE) fuel cell, the phosphoric acid fuel cell, and the molten carbonate fuel cell. The conceptual system configuration in Figure 29 is not affected by type of fuel cell. The conceptual configuration includes a fuel processor (such as a methanol reformer, or a JP-4 reformer) to convert a hydrocarbon fuel to a hydrogen-rich gas. The hydrogen and oxygen (from the air input) react electrochemically to produce DC power and waste heat. The DC power is transformed to AC with a power conditioner (inverter).

Technology Status. Phosphoric acid fuel cells are expected to be commercially available in the capacity range of 1.5 to 100.0 kW starting in 1985. They are expected to be commercially available in the capacity range of 250.0 to 5000.0 kW starting in 1990. Molten carbonate fuel cells are expected to be commercially available at capacities of 250.0 and 500.0 kW starting in 1990. They are expected to be commercially available in the capacity range of 750.0 to 5000.0 kW starting in 2000. Solid polymer electrolyte fuel cells are expected to be commercially available in the capacity range of 1.5 to 30.0 kW starting in 2000. The primary factor delaying earlier implementation of advanced fuel cell technology is that the limited available R&D funds are being used to support the phosphoric acid fuel cell commercialization.

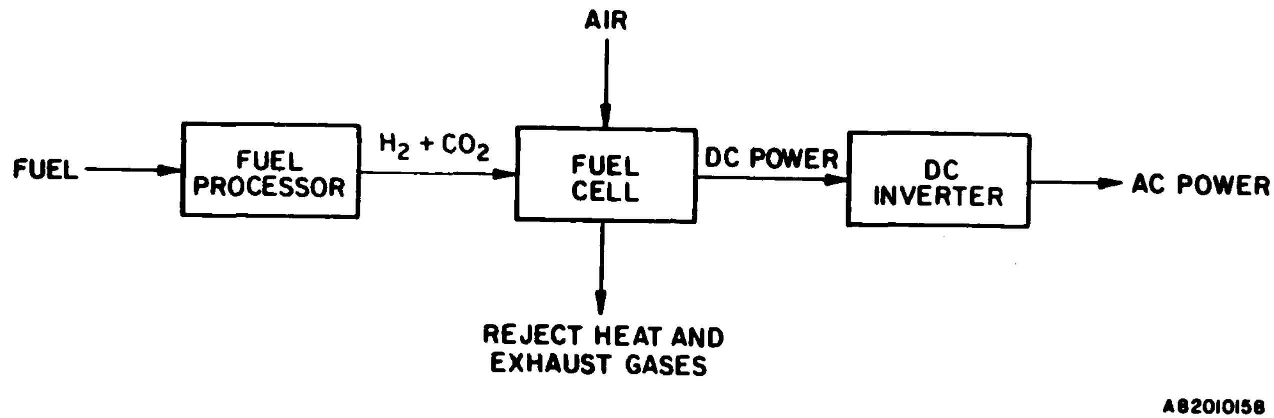

Figure 29. FUEL CELL SYSTEMS

Type. Fuel cell system "Type" parameter values are in Table 38. Below 100 kW, fuel cell systems are mobile; above 250 kW, they are fixed.

Table 38. FUEL CELL SYSTEM TYPE
(Mobile, Transportable, Fixed)

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID	MOLTEN CARBONATE	SOLID POLYMER
1.5	1980	NCA	NCA	NCA
	1985	M	NCA	NCA
	1990	M	NCA	NCA
	2000	M	NCA	M
5.0	1980	NCA	NCA	NCA
	1985	M	NCA	NCA
	1990	M	NCA	NCA
	2000	M	NCA	M
20.0	1980	NCA	NCA	NCA
	1985	M	NCA	NCA
	1990	M	NCA	NCA
	2000	M	NCA	M
30.0	1980	NCA	NCA	NCA
	1985	M	NCA	NCA
	1990	M	NCA	NCA
	2000	M	NCA	M
60.0	1980	NCA	NCA	NCA
	1985	M	NCA	NCA
	1990	M	NCA	NCA
	2000	M	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	T	NCA	NCA
	1990	T	NCA	NCA
	2000	T	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	T	T	NCA
	2000	T	T	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	F	F	NCA
	2000	F	F	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	F	NCA	NCA
	2000	F	F	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	F	NCA	NCA
	2000	F	F	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	F	NCA	NCA
	2000	F	F	NCA

System Acquisition Cost. Fuel cell "System Acquisition Cost" parameter values are presented in Table 39 and in Figure 30.

Table 39. FUEL CELL SYSTEM ACQUISITION COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID	MOLTEN CARBONATE	SOLID POLYMER
1.5	1980	NCA	NCA	NCA
	1985	2.25E03	NCA	NCA
	1990	1.50E03	NCA	NCA
	2000	9.00E02	NCA	1.28E03
5.0	1980	NCA	NCA	NCA
	1985	7.50E03	NCA	NCA
	1990	5.00E03	NCA	NCA
	2000	3.00E03	NCA	4.25E03
20.0	1980	NCA	NCA	NCA
	1985	3.00E04	NCA	NCA
	1990	2.00E04	NCA	NCA
	2000	1.20E04	NCA	1.70E04
30.0	1980	NCA	NCA	NCA
	1985	4.50E04	NCA	NCA
	1990	3.00E04	NCA	NCA
	2000	1.80E04	NCA	2.55E04
60.0	1980	NCA	NCA	NCA
	1985	9.00E04	NCA	NCA
	1990	6.00E04	NCA	NCA
	2000	3.60E04	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	1.50E05	NCA	NCA
	1990	1.00E05	NCA	NCA
	2000	6.0E04	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.25E05	2.50E05	NCA
	2000	1.25E05	1.25E05	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.50E05	3.00E05	NCA
	2000	2.00E05	2.00E05	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.75E05	NCA	NCA
	2000	3.00E05	3.00E05	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	5.00E05	NCA	NCA
	2000	4.00E05	4.00E05	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.50E06	NCA	NCA
	2000	2.0E06	2.00E06	NCA

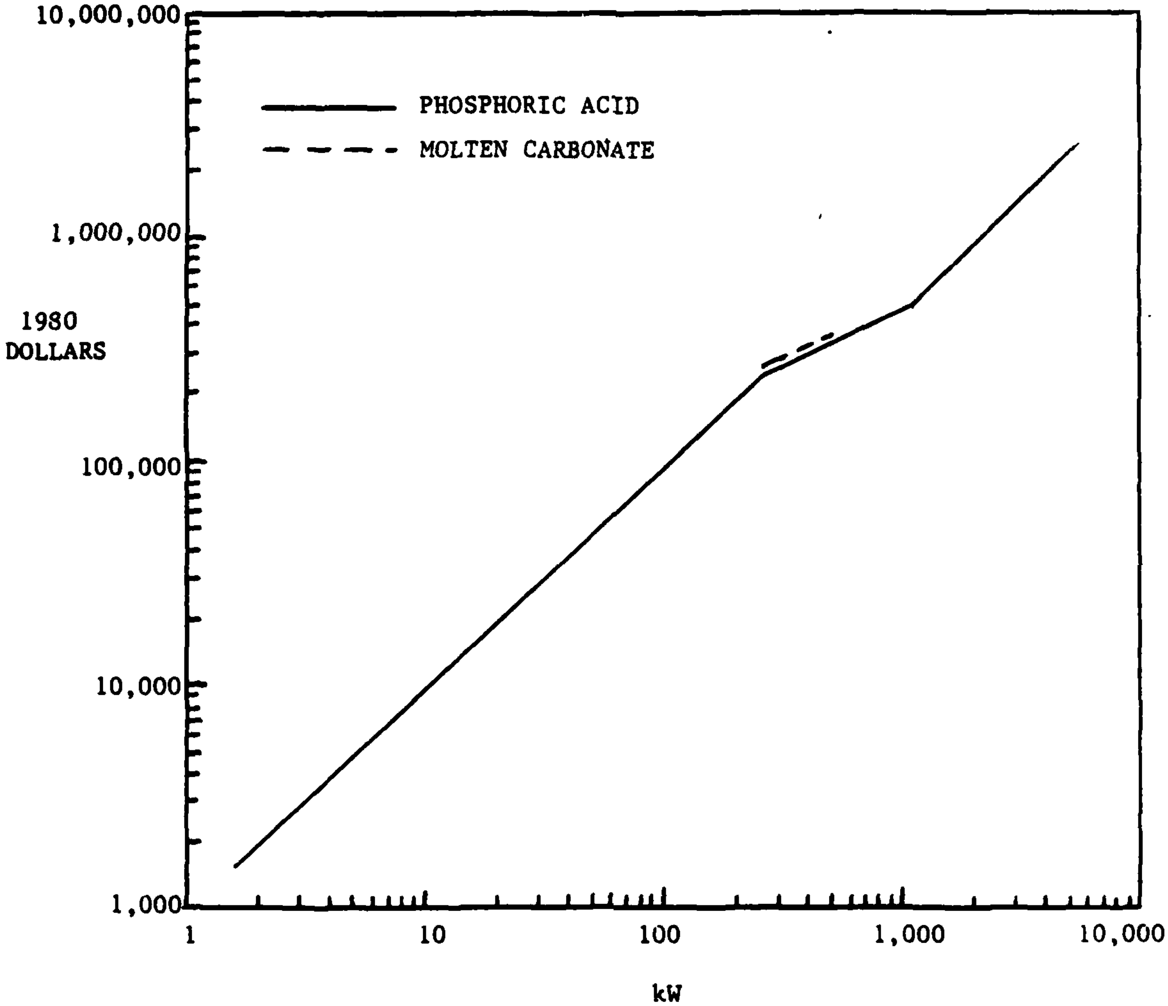

Figure 30. FUEL CELL SYSTEM ACQUISITION COST

Annual Operations and Maintenance Costs. Fuel cell "Annual Operations and Maintenance Costs" parameter values are presented in Table 40 and in Figure 31.

Table 40. FUEL CELL ANNUAL OPERATIONS AND MAINTENANCE COSTS (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID	MOLTEN CARBONATE	SOLID POLYMER
1.5	1980	NCA	NCA	NCA
	1985	2.25E02	NCA	NCA
	1990	1.50E02	NCA	NCA
	2000	9.00E01	NCA	1.28E02
5.0	1980	NCA	NCA	NCA
	1985	7.50E02	NCA	NCA
	1990	5.00E02	NCA	NCA
	2000	3.00E02	NCA	4.25E02
20.0	1980	NCA	NCA	NCA
	1985	3.00E03	NCA	NCA
	1990	2.00E03	NCA	NCA
	2000	1.20E03	NCA	1.70E03
30.0	1980	NCA	NCA	NCA
	1985	4.50E03	NCA	NCA
	1990	3.00E03	NCA	NCA
	2000	1.80E03	NCA	2.55E03
60.0	1980	NCA	NCA	NCA
	1985	9.00E03	NCA	NCA
	1990	6.00E03	NCA	NCA
	2000	3.60E03	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	1.50E04	NCA	NCA
	1990	1.00E04	NCA	NCA
	2000	6.00E03	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.25E04	2.50E04	NCA
	2000	1.25E04	1.25E04	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.50E04	3.00E04	NCA
	2000	2.00E04	2.00E04	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.75E04	NCA	NCA
	2000	3.00E04	3.00E04	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	5.00E04	NCA	NCA
	2000	4.00E04	4.00E04	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.50E05	NCA	NCA
	2000	2.00E05	2.00E05	NCA

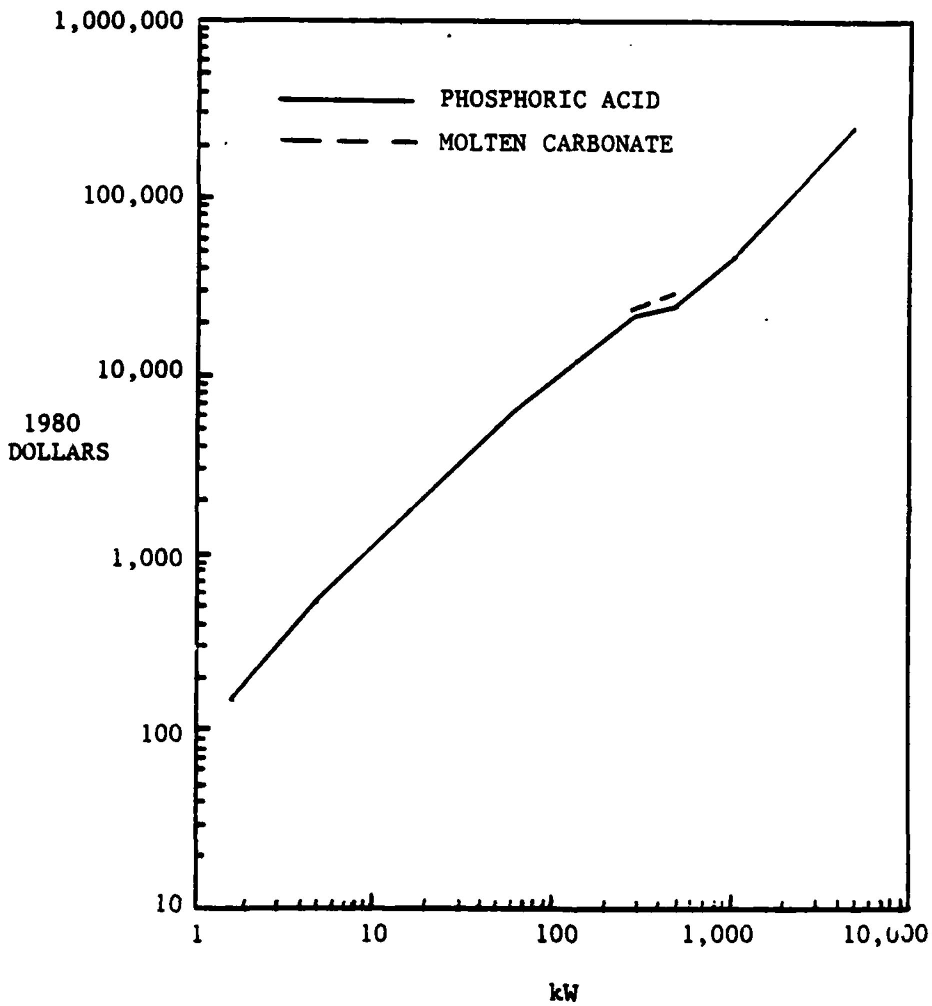

Figure 31. FUEL CELL ANNUAL OPERATIONS AND MAINTENANCE COSTS

System Efficiency. Fuel cell "System Efficiency" parameter values are presented in Table 41 and in Figure 32. The overall efficiency (thermal and electrical) of each of the fuel cell types can be affected by the capability to utilize the waste heat from the system. Molten carbonate fuel cells operate at temperatures greater than phosphoric acid fuel cells (about 900 to 1400°F compared to 150 to 400°F). This permits a bottoming cycle to be used with the molten carbonate fuel cell for further electrical production. The solid polymer electrolyte fuel cell operates at lower temperatures than the phosphoric acid fuel cell and provides the least opportunities for waste heat utilization.

Table 41. FUEL CELL SYSTEM EFFICIENCY (%)

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID	MOLTEN CARBONATE	SOLID POLYMER
1.5	1980	NCA	NCA	NCA
	1985	35	NCA	NCA
	1990	38	NCA	NCA
	2000	40	NCA	50
5.0	1980	NCA	NCA	NCA
	1985	35	NCA	NCA
	1990	38	NCA	NCA
	2000	40	NCA	50
20.0	1980	NCA	NCA	NCA
	1985	35	NCA	NCA
	1990	38	NCA	NCA
	2000	40	NCA	50
30.0	1980	NCA	NCA	NCA
	1985	35	NCA	NCA
	1990	40	NCA	NCA
	2000	42	NCA	50
60.0	1980	NCA	NCA	NCA
	1985	35	NCA	NCA
	1990	40	NCA	NCA
	2000	42	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	38	NCA	NCA
	1990	40	NCA	NCA
	2000	45	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	40	45	NCA
	2000	45	50	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	40	48	NCA
	2000	45	52	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	40	NCA	NCA
	2000	45	52	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	40	NCA	NCA
	2000	45	52	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	40	NCA	NCA
	2000	45	52	NCA

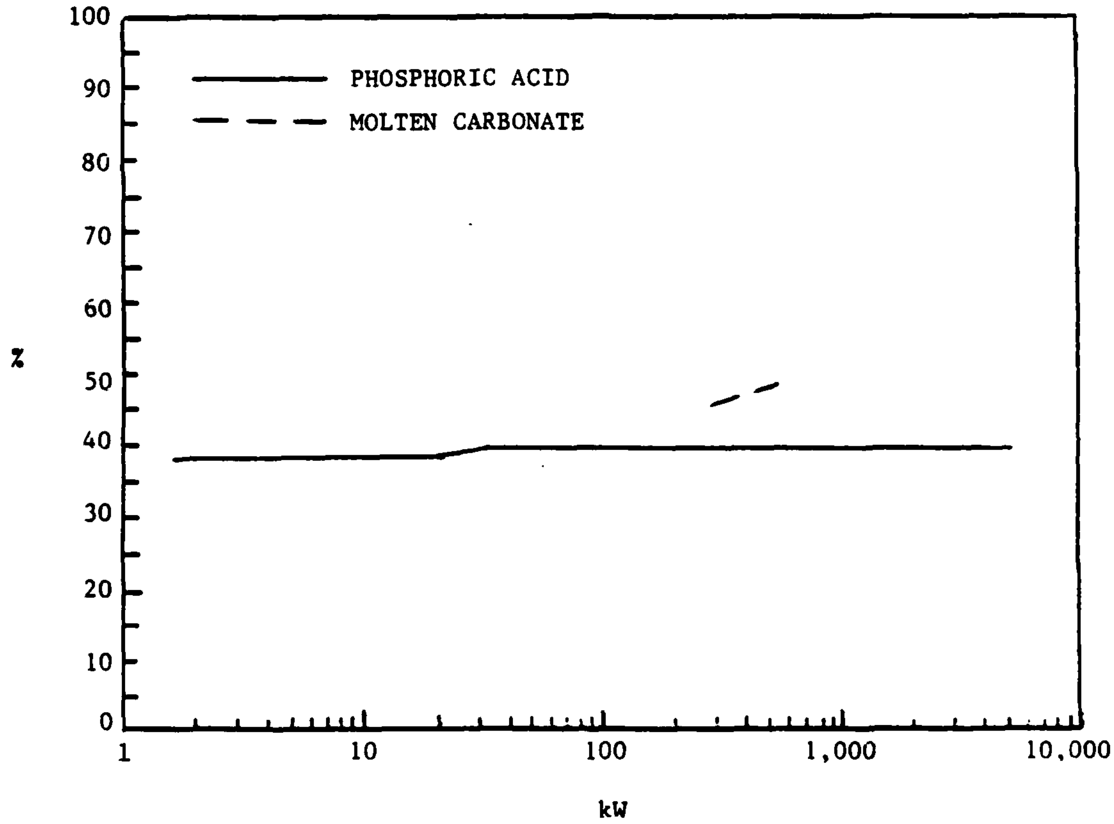

Figure 32. FUEL CELL SYSTEM EFFICIENCY

Fuel Consumption. Fuel cell "Fuel Consumption" parameter values are presented in Table 42 and in Figure 33.

Table 42. FUEL CELL FUEL CONSUMPTION

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID (gal/hr)	MOLTEN CARBONATE (gal/hr)	SOLID POLYMER (gal/hr)
1.5	1980	NCA	NCA	NCA
	1985	0.11	NCA	NCA
	1990	0.10	NCA	NCA
	2000	0.10	NCA	0.08
5.0	1980	NCA	NCA	NCA
	1985	0.37	NCA	NCA
	1990	0.34	NCA	NCA
	2000	0.32	NCA	0.26
20.0	1980	NCA	NCA	NCA
	1985	1.47	NCA	NCA
	1990	1.36	NCA	NCA
	2000	1.30	NCA	1.04
30.0	1980	NCA	NCA	NCA
	1985	2.22	NCA	NCA
	1990	2.04	NCA	NCA
	2000	1.95	NCA	1.56
60.0	1980	NCA	NCA	NCA
	1985	4.43	NCA	NCA
	1990	4.09	NCA	NCA
	2000	3.91	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	6.82	NCA	NCA
	1990	6.49	NCA	NCA
	2000	5.76	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	16.2	14.5	NCA
	2000	14.4	13.0	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	32.4	27.0	NCA
	2000	28.7	25.0	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	48.6	NCA	NCA
	2000	43.1	37.5	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	65.2	NCA	NCA
	2000	57.4	49.9	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	324	NCA	NCA
	2000	287	250	NCA

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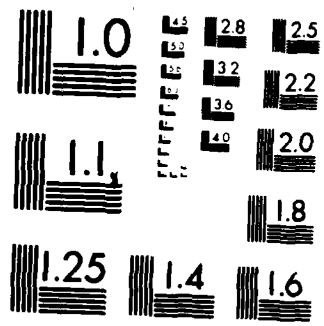

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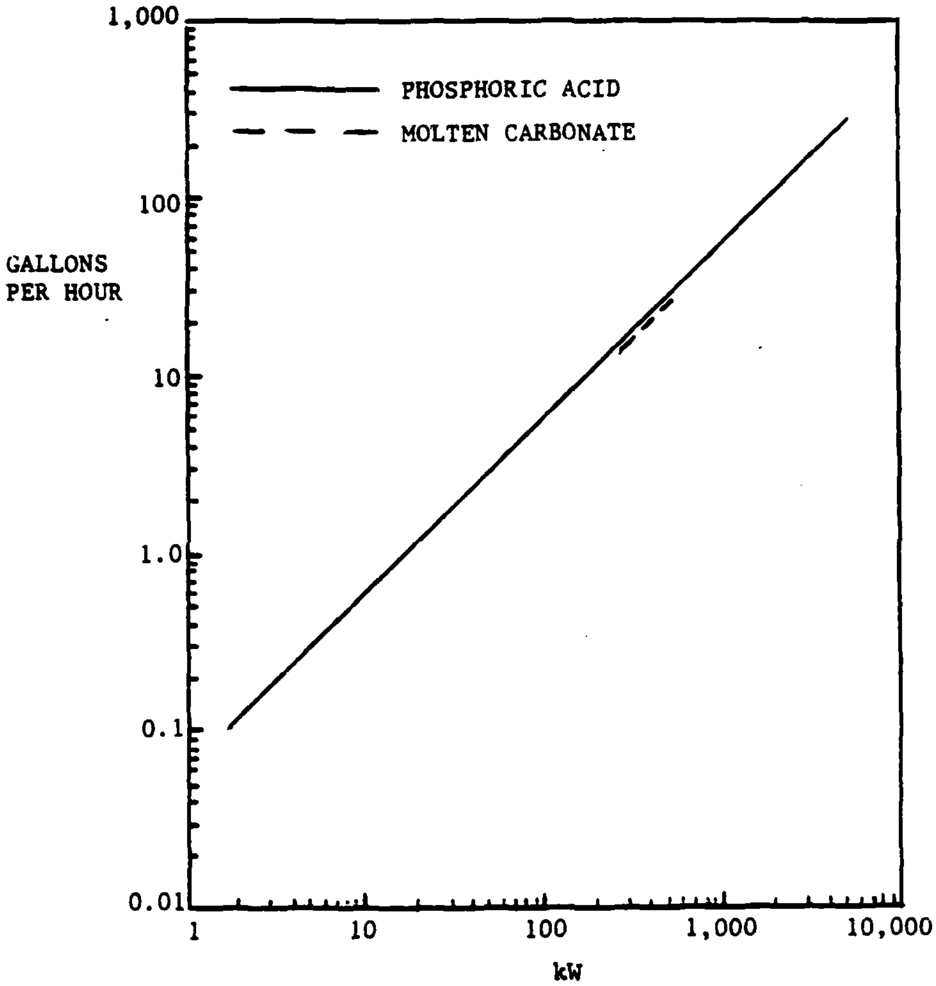

Figure 33. FUEL CELL FUEL CONSUMPTION

Annual Fuel Cost. Fuel cell "Annual Fuel Cost" parameter values (based on 1980 dollars and no real escalation) are presented in Table 43 and in Figure 34.

Table 43. FUEL CELL ANNUAL FUEL COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID	MOLTEN CARBONATE	SOLID POLYMER
1.5	1980	NCA	NCA	NCA
	1985	1.01E03	NCA	NCA
	1990	9.35E02	NCA	NCA
	2000	8.91E02	NCA	7.12E02
5.0	1980	NCA	NCA	NCA
	1985	3.38E03	NCA	NCA
	1990	3.11E03	NCA	NCA
	2000	2.97E03	NCA	2.37E03
20.0	1980	NCA	NCA	NCA
	1985	1.35E04	NCA	NCA
	1990	1.24E04	NCA	NCA
	2000	1.19E04	NCA	9.53E03
30.0	1980	NCA	NCA	NCA
	1985	2.03E04	NCA	NCA
	1990	1.87E04	NCA	NCA
	2000	1.79E04	NCA	1.43E04
60.0	1980	NCA	NCA	NCA
	1985	4.06E04	NCA	NCA
	1990	3.74E04	NCA	NCA
	2000	3.58E04	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	6.24E04	NCA	NCA
	1990	5.94E04	NCA	NCA
	2000	5.27E04	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.48E05	1.32E05	NCA
	2000	1.31E05	1.19E05	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.96E05	2.47E05	NCA
	2000	2.63E05	2.28E05	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	4.45E05	NCA	NCA
	2000	3.94E05	3.43E05	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	5.97E05	NCA	NCA
	2000	5.25E05	4.57E05	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2.96E06	NCA	NCA
	2000	2.63E06	2.28E06	NCA

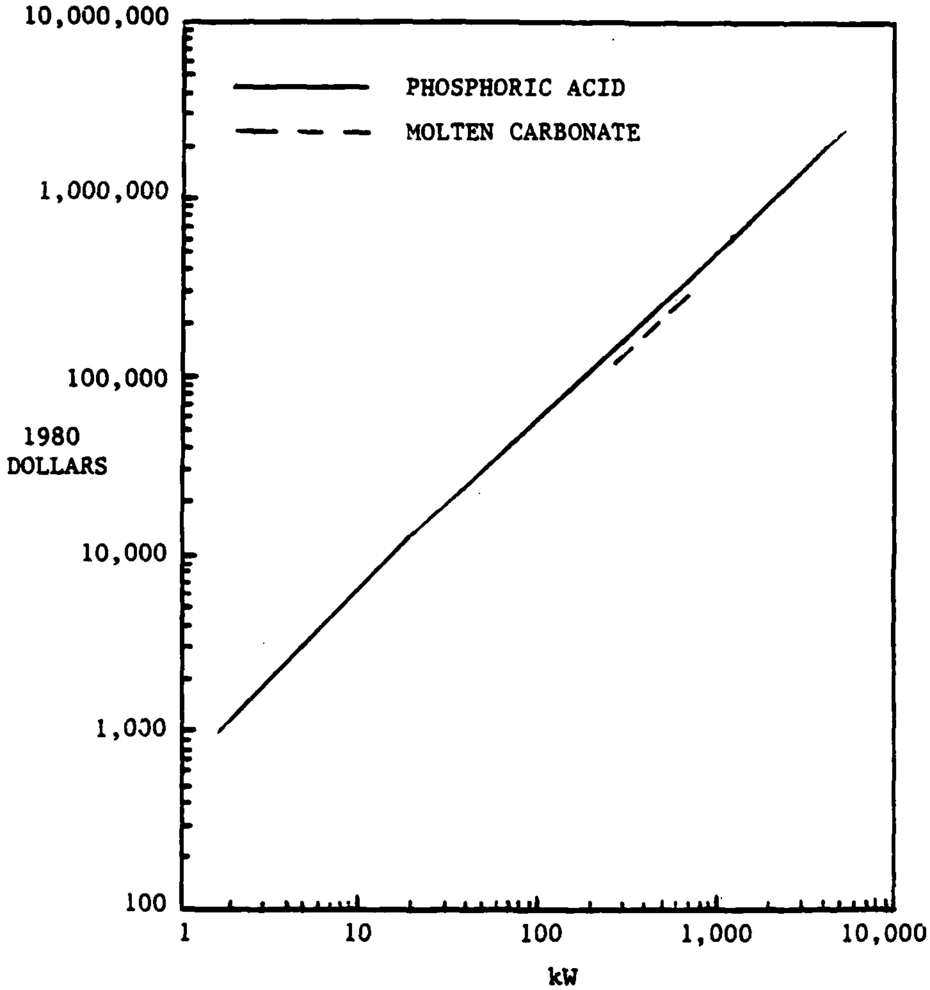

Figure 34. FUEL CELL ANNUAL FUEL COST

Life-Cycle Cost. Fuel cell "Life-Cycle Cost" parameter values are presented in Table 44 in Figure 35. The life-cycle cost includes the cost of replacing the fuel cell stack every 5 years over the 20 year operating life of the system.

Table 44. FUEL CELL LIFE CYCLE COST, 0% FUEL ESCALATION (1980 CENTS/kWh)

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID	MOLTEN CARBONATE	SOLID POLYMER
1.5	1980	NCA	NCA	NCA
	1985	5.40	NCA	NCA
	1990	4.56	NCA	NCA
	2000	3.91	NCA	3.56
5.0	1980	NCA	NCA	NCA
	1985	5.41	NCA	NCA
	1990	4.53	NCA	NCA
	2000	3.91	NCA	3.56
20.0	1980	NCA	NCA	NCA
	1985	5.41	NCA	NCA
	1990	4.52	NCA	NCA
	2000	3.92	NCA	3.57
30.0	1980	NCA	NCA	NCA
	1985	5.41	NCA	NCA
	1990	4.54	NCA	NCA
	2000	3.93	NCA	3.57
60.0	1980	NCA	NCA	NCA
	1985	5.41	NCA	NCA
	1990	4.54	NCA	NCA
	2000	3.93	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	5.13	NCA	NCA
	1990	4.38	NCA	NCA
	2000	3.55	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	4.25	4.02	NCA
	2000	3.42	3.16	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.78	3.37	NCA
	2000	3.31	2.93	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.79	NCA	NCA
	2000	3.31	2.94	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.81	NCA	NCA
	2000	3.31	2.93	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.43	NCA	NCA
	2000	3.31	2.93	NCA

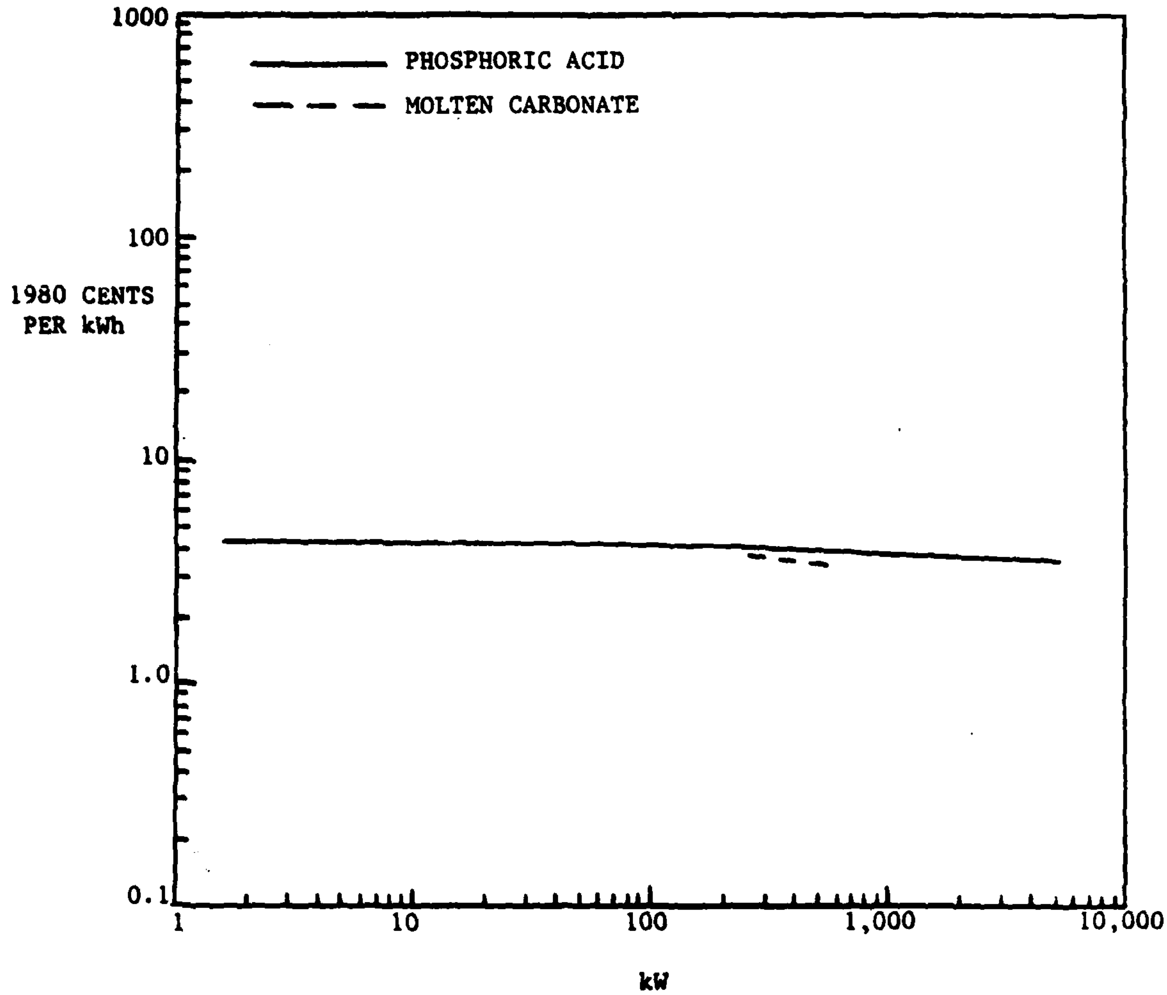

Figure 35. FUEL CELL LIFE-CYCLE COST, 0% FUEL ESCALATION

System Volume. Fuel cell "System Volume" parameter values are presented in Table 45.

Table 45. FUEL CELL SYSTEM VOLUME (CUBIC FEET)

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID	MOLTEN CARBONATE	SOLID POLYMER
1.5	1980	NCA	NCA	NCA
	1985	3.6	NCA	NCA
	1990	3.0	NCA	NCA
	2000	3.0	NCA	3.0
5.0	1980	NCA	NCA	NCA
	1985	12.0	NCA	NCA
	1990	10.0	NCA	NCA
	2000	10.0	NCA	10.0
20.0	1980	NCA	NCA	NCA
	1985	45	NCA	NCA
	1990	40	NCA	NCA
	2000	40	NCA	40.0
30.0	1980	NCA	NCA	NCA
	1985	210	NCA	NCA
	1990	180	NCA	NCA
	2000	180	NCA	180
60.0	1980	NCA	NCA	NCA
	1985	420	NCA	NCA
	1990	340	NCA	NCA
	2000	340	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	700	NCA	NCA
	1990	650	NCA	NCA
	2000	650	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	2000	2000	NCA
	2000	2000	2000	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	4.0E03	4.0E03	NCA
	2000	4.0E03	4.0E03	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	6.0E03	NCA	NCA
	2000	6.0E03	6.0E03	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.0E04	NCA	NCA
	2000	1.0E04	1.0E04	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.25E05	NCA	NCA
	2000	1.25E05	1.25E05	NCA

System Weight. Fuel cell "System Weight" parameter values are presented in Table 46.

Table 46. FUEL CELL SYSTEM WEIGHT (POUNDS)

POWER OUTPUT LEVEL, KW	YEAR	PHOSPHORIC ACID	MOLTEN CARBONATE	SOLID POLYMER
1.5	1980	NCA	NCA	NCA
	1985	2.5E02	NCA	NCA
	1990	2.0E02	NCA	NCA
	2000	2.0E02	NCA	2.0E02
5.0	1980	NCA	NCA	NCA
	1985	8.75E02	NCA	NCA
	1990	7.0 E02	NCA	NCA
	2000	7.0 E02	NCA	7.0E02
20.0	1980	NCA	NCA	NCA
	1985	3.5E03	NCA	NCA
	1990	2.8E03	NCA	NCA
	2000	2.8E03	NCA	2.8E03
30.0	1980	NCA	NCA	NCA
	1985	5.2E03	NCA	NCA
	1990	4.2E03	NCA	NCA
	2000	4.2E03	NCA	4.2E03
60.0	1980	NCA	NCA	NCA
	1985	1.0E04	NCA	NCA
	1990	8.0E03	NCA	NCA
	2000	8.0E03	NCA	NCA
100.0	1980	NCA	NCA	NCA
	1985	1.8E04	NCA	NCA
	1990	1.36E04	NCA	NCA
	2000	1.36E04	NCA	NCA
250.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.4E04	3.4E04	NCA
	2000	3.4E04	3.4E04	NCA
500.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	7.2E04	7.2E04	NCA
	2000	7.2E04	7.2E04	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.2E05	NCA	NCA
	2000	1.2E05	1.2E05	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.6E05	NCA	NCA
	2000	1.6E05	1.6E05	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	8.0E05	NCA	NCA
	2000	8.0E05	8.0E05	NCA

Fuel Requirements and Capabilities. The designated fuel is JP-4. Since fuel cells actually run on the hydrogen component of the fuel, they may have multi-fuel capabilities, at least as consistent with the fuel processor technology that is available to convert the fuel into a form suitable for fuel cell use. The fuel cell is not sensitive to the type of fuel assuming the fuel produced by the fuel processor does not contain impurities which can affect the operation of the fuel cell. Fuel cells are affected to various degrees by impurities such as CO, H_2S, SO_2, Cl_2, NO_x, and NH_3. Molten carbonate cells are expected to require sulfur removal down to 1 ppm. Phosphoric acid fuel cells require CO concentrations of less than 4% and usually require a shift reactor to convert CO from the fuel processor and H_2O to CO_2 and H_2.

Fuel specifications are very restrictive because unless impurity levels are very low, the catalyst in the fuel processor may be ruined.

Only fuel processors for methanol are current technology. Fuel processors for JP-4 and diesel are under development. Although methanol is not a logistic fuel, it may be a preferred fuel cell fuel because it reduces fuel processor complexity.

Start-up Time. Phosphoric acid fuel cell "Start-up Time" is 40 minutes at 1.5 and 5.0 kW, 45 minutes at 20.0 kW, 60 minutes at 30.0 and 60.0 kW, 120 minutes at 100.0 and 250.0 kW, 150 minutes at 500.0 and 750.0 kW, and 180 minutes at 1000.0 and 5000.0 kW. Molten carbonate fuel cell "Start-up Time" is 180 minutes at 250.0 and 500.0 kW, and 200 minutes at 750.0, 1000.0, and 5000.0 kW. Solid polymer electrolyte fuel cell "start-up time" is 40 minutes. Small capacity fuel cells using methanol fuel can have shorter start-up times because the fuel processor is not massive and may be brought up to the low reforming temperature quickly with increased fuel consumption. JP-4 fuel processors, technically known as "reformers," have longer start-up times because they operate at high temperatures, and start-up operations must be slow and carefully sequenced to avoid thermal shock of catalyst support structure, carbon formation, and potential catalyst inactivations.

Shutdown Time. Phosphoric acid fuel cell "Shutdown Time" is 30 minutes for capacities of 1.5 kW to 100 kW, 60 minutes at 250.0 kW, 90 minutes at capacities of 500.0 and 750.0 kW, 120 mintues at 1000.0 kW, and 150 minutes at 5000.0 kW. Molten carbonate fuel cell "shutdown time" is 150 minutes at

250.0 kW, 180 minutes at 500.0 and 750.0 kW, 200 minutes at 1000.0 kW, and 240 minutes at 5000.0 kW. Solid polymer electrolyte fuel cell "shutdown time" is 30 minutes.

Reliability. Fuel cell "Reliability" has an ordinal score of 4 indicating moderate reliability. Fuel cells are somewhat more reliable than diesels, mainly because of fewer moving parts.

Environmental Constraints. Fuel cells have an ordinal score of 5 indicating minimum potential environmental constraints. Fuel cells have less environmental constraints than diesels. Noise may be minor constraint.

Location Constraints. Fuel cells have an ordinal score of 4 indicating moderate locational constraints. Fuel cells have less locational constraints than diesels, although they still may have fuel availability and delivery problems.

Operation Constraints. Fuel cells have an ordinal score of 3 indicating average turn-down capability. Diesels have somewhat less operational constraints. Fuel cells have very limited overload capability.

Photovoltaic Energy Conversion Systems

Three types of photovoltaic energy conversion systems were considered: passively cooled flat plate, photoelectrochemical, and actively cooled. The three systems are diagramed schematically in Figure 36. A photovoltaic system consists of modules, which are integrated arrays of cells; structures to support and interconnect modules; and balance of system components (controls, batteries, inverters) to produce an entity capable of serving a load. Passive and active designs were based on performance characteristics as reported in the data base for single-crystal silicon photovoltaic cells applied to flat-plate and concentrating arrays since they are the primary commercially available photovoltaic technology. Actively cooled photovoltaic systems are interpreted as defining concentrating collectors that require active cooling of photovoltaic cells to maintain efficient photovoltaic solar energy conversion performance. Flat-plate and photoelectrochemical photovoltaic systems differ

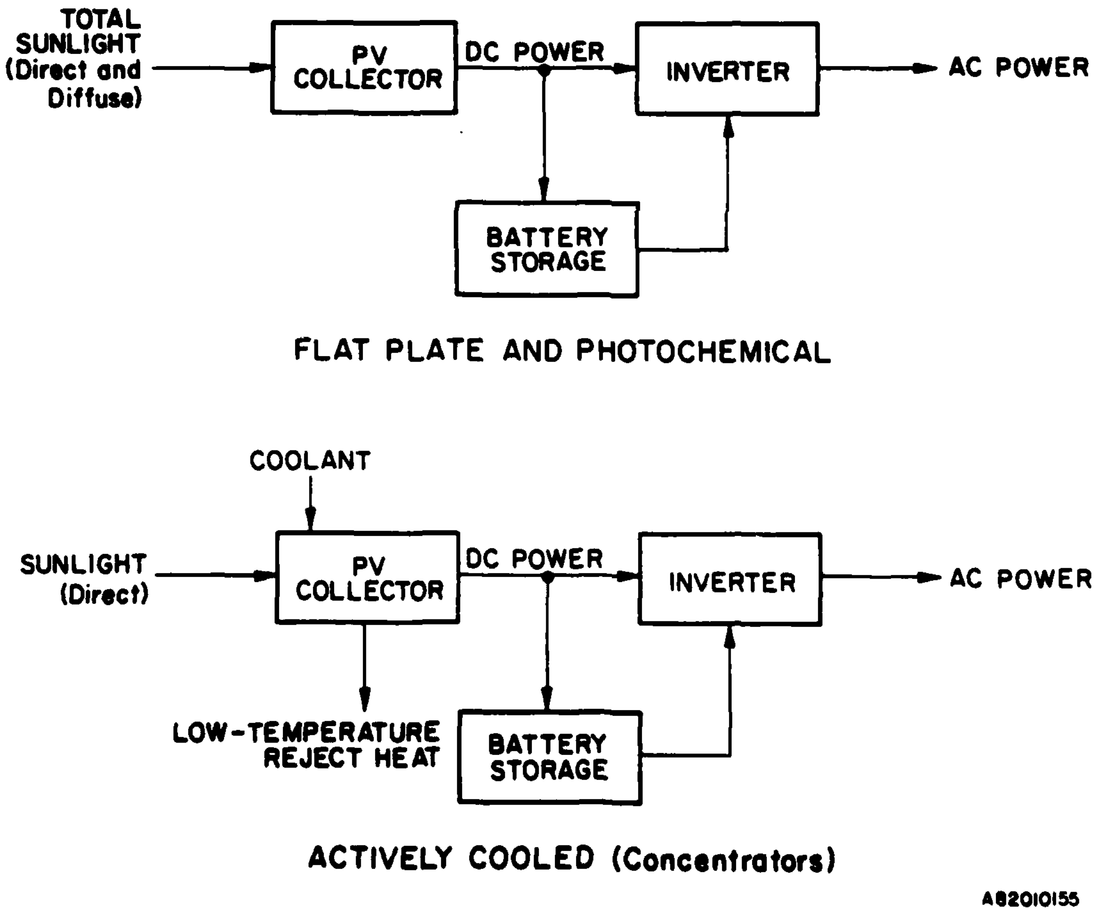

Figure 36. PHOTOVOLTAIC SYSTEMS

from actively cooled, concentrating photovoltaic systems in two ways. The first difference is that flat-plate and photoelectrochemical systems utilize the total insolation — that is, the direct or specular component of sunlight plus indirect or diffuse sunlight. In the most general case, photoelectrochemical systems may be employed with sunlight concentration. Concentrating photovoltaic systems accept only the direct component of sunlight. In addition, because of the use of concentrating optics they must track the sun in at least one axis to keep the sun's image properly focused upon the photovoltaic cells. Flat-plate and photoelectrochemical systems are generally fixed and do not need to track the sun, although sun tracking systems may be employed. Because energy production of photovoltaic systems is dependent on the amount of solar energy falling on the collector, actively cooled systems suffer somewhat lower performance than fixed, flat-plate photovoltaic systems because the direct component of insolation is always less than the total insolation. However, this deficiency is substantially overcome by tracking the sun so that insolation availability is substantially similar for both fixed and tracking systems. The second difference is that flat-plate and photoelectrochemical systems operate near ambient temperatures, while concentrating photovoltaics are actively cooled to maintain cell temperature at efficient operating conditions. Hence, concentrating systems are able to provide low-temperature thermal energy (<180°F) for other uses such as domestic hot water or space heating.

Photovoltaic energy systems require batteries as a means of electrical energy storage because of the realities of the day/night cycle and the transient nature of daytime solar availability due to the movement of the sun in the sky and the presence of clouds. Inverters are necessary to convert the DC output of photovoltaic systems and batteries to utility-quality AC power.

Sizing photovoltaic arrays — that is, the determination of array area and battery capacity to produce continuous power output — is complicated by the fact that photovoltaic systems are quite sensitive to site. In a high insolation site such as in the Southwest, a considerably smaller array is required than in a Midwest or Neareast location. The design method used is not directly applicable to concentrating systems, but was modified as necessary to size these systems with reasonable accuracy. The design method predicted the required array size to produce a continuous 1 kW output. Note that characteristic data for photovoltaic energy conversion systems are frequently

reported on a peak kilowatt (kW_p) basis. This is not the same as the average kilowatt basis describing conventional energy conversion systems such as diesels. Although this is the conventional method of reporting the performance of photovoltaic technologies, it is thus difficult to compare different energy technologies on the same basis. Photovoltaic conversion device performance is established under "peak insolation" conditions of one kilowatt per square meter. Because photovoltaic systems are modular, system size for larger outputs is a linear function of the desired power requirement. (For example, a 5000 kW_e system is 5000 times the size of a 1 kW system.) Designs were prepared for continuous power systems for Albuquerque and Madison insolation to bracket insolation regimes. A linear interpolation was performed on the resulting photovoltaic array area and battery capacity to an average site because the data base developed in this study can only accept parameters of one representative case.

Battery storage capacity was sized such that no energy was wasted during the design month, and all array output may thus be applied to the load. Lead-acid battery technology with characteristic parameters as reported in the data base was used as the means of electrical energy storage.

The results of the photovoltaic array sizing analysis has some implications that should be recognized. Photovoltaic systems for continuous duty are designed to produce power outputs of the desired value, but the data base user must realize that even with the presence of energy storage in the system inherent statistical variations in insolation availability may lead to occasional power outages. Outages are most likely to occur (albeit infrequently) during the low-insolation winter months. Because the photovoltaic system is considerably oversized to guarantee continuous power output under worst-month insolation conditions, significantly greater annual power output (> 8760 kWH_e/year) is possible if a load and/or energy storage exists to make use of the system output.

Flat-Plate Photovoltaic System Design

Assumptions and data input values for this design are summarized below:

- Sites considered — Albuquerque, New Mexico, and Madison, Wisconsin
- Photovoltaic system sized for worst-month insolation on tilted collector surface

- Collector tilted at local latitude and facing due south
- National average daily December insolation on south-facing collector at 45° tilt angle — 1204 Btu/ft^2 day
- Reported photovoltaic array efficiency at 82.4°F for single-crystal, flat-plate collector — 10.6%
- Assumed power conditioning system efficiency — 90%
- Reported battery efficiency (lead-acid technology) — 79%
- Reported allowable battery depth of discharge — 80%
- Average daily total insolation on tilted collector:

  a. Madison — 987.7 Btu/ft^2 day

  b. Albuquerque — 1906.4 Btu/ft^2 day

- Flat-plate collector tilt angle:

  a. Madison — 45°

  b. Albuquerque — 35°

The results of the analyses are as follows:

- Madison flat-plate photovoltaic array area — 888 ft^2/kW
- Madison required battery storage capacity — 25.4 kWh_e/kW
- Albuquerque flat-plate photovoltaic array area — 444 ft^2/kW
- Albuquerque required battery storage capacity — 22.9 kWh_e/kW

<u>Actively Cooled (Concentrating) Photovoltaic System Design</u>

Assumptions and data input values are summarized below:

- Photovoltaic system sized to worst month insolation in plane of collector
- Photovoltaic collector is assumed to be oriented east-west and tracking about a horizontal axis
- National average winter insolation in plane of collector — 1109 Btu/ft^2 day
- Reported concentrating photovoltaic array efficiency — 9.1%
- Average daily insolation in plane of collector:

  a) Madison — 1078.3 Btu/ft^2 day (November)

  b) Albuquerque — 1842.8 Btu/ft^2 day (February)

The results of the analyses are as follows:

- Madison concentrating photovoltaic array area — 1097 ft^2/kW
- Madison required battery storage capacity — 25.4 kWh/kW
- Albuquerque concentrating photovoltaic array area — 634.1 ft^2/kW
- Albuquerque required battery storage capacity — 24.1 kWh/kW

The generic design of flat-plate and concentrating photovoltaic energy conversion system was determined by linear interpolation on the primary independent variable characterizing such systems — the average insolation in the worst month. The results are as follows:

- Generic flat-plate photovoltaic array area — 783.5 ft^2/kW
- Generic required battery storage capacity for flat-plate photovoltaic systems — 24.8 kWh_e/kW
- Generic concentrating photovoltaic array area — 1078 ft^2/kW
- Generic required battery storage capacity for concentrating photovoltaic systems — 26.0 kWh/kW

Therefore, the parameters for the photovoltaic system as reported in the data base are based on the above array and storage requirements for a 1 kW continuous system because the photovoltaic systems are modular.

Technology Status. Flat-plate photovoltaic systems are currently available in capacities of 1.5 to 100.0 kW. In 1985, flat-plate photovoltaic systems are expected to be available in capacities up to and including 500.0 kW. In 1990 flat-plate photovoltaic systems are expected to be available in capacities up to and including 750.0 kW. In 2000, flat-plate photovoltaics are expected to be available in all capacities.

Actively cooled photovoltaic systems are currently available in capacities of 1.5 to 30.0 kW. In 1985 they are expected to be available at capacities up to and including 250.0 kW. In 1990 actively cooled photovoltaic systems are expected to be available in capacities through 750.0 kW. In 2000 they are expected to be available in capacities through 1000.0 kW. Photochemical photovoltaic systems are expected to be available at capacities of 1.5 to 30.0 kW in 2000. Current research efforts are focusing on reducing the cost of producing photovoltaics.

Type. Photovoltaic system "Type" parameter values are presented in Table 47. At the output levels considered, most continuous duty photovoltaic systems will be fixed.

Table 47. PHOTOVOLTAIC SYSTEM TYPE
(Mobile, Transportable, Fixed)

POWER OUTPUT LEVEL, KW	YEAR	FLAT PLATE	ACTIVELY COOLED	PHOTOCHEMICAL
1.5	1980	T	F	NCA
	1985	M	F	NCA
	1990	M	F	NCA
	2000	M	F	T
5.0	1980	F	F	NCA
	1985	F	F	NCA
	1990	F	F	NCA
	2000	F	F	F
20.0	1980	F	F	NCA
	1985	F	F	NCA
	1990	F	F	NCA
	2000	F	F	F
30.0	1980	F	F	NCA
	1985	F	F	NCA
	1990	F	F	NCA
	2000	F	F	F
60.0	1980	F	NCA	NCA
	1985	F	F	NCA
	1990	F	F	NCA
	2000	F	F	NCA
100.0	1980	F	NCA	NCA
	1985	F	F	NCA
	1990	F	F	NCA
	2000	F	F	NCA
250.0	1980	NCA	NCA	NCA
	1985	F	F	NCA
	1990	F	F	NCA
	2000	F	F	NCA
500.0	1980	NCA	NCA	NCA
	1985	F	NCA	NCA
	1990	F	F	NCA
	2000	F	F	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	F	F	NCA
	2000	F	F	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	F	NCA	NCA
	2000	F	F	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	F	NCA	NCA

<u>System Acquisition Cost</u>. Photovoltaic "System Acquisition Cost" parameter values are presentd in Table 48 and in Figure 37.

Table 48. PHOTOVOLTAIC SYSTEM ACQUISITION COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	FLAT PLATE	ACTIVELY COOLED	PHOTOCHEMICAL
1.5	1980	2.84E05	4.15E05	NCA
	1985	2.45E05	3.57E05	NCA
	1990	2.07E05	3.03E05	NCA
	2000	2.07E05	3.03E05	2.07E05
5.0	1980	9.48E05	1.38E06	NCA
	1985	8.15E05	1.19E06	NCA
	1990	6.92E05	1.01E06	NCA
	2000	6.92E05	1.01E06	6.92E05
20.0	1980	3.79E06	5.54E06	NCA
	1985	3.26E06	4.76E06	NCA
	1990	2.77E06	4.04E06	NCA
	2000	2.77E06	4.04E06	2.77E06
30.0	1980	5.69E06	8.31E06	NCA
	1985	4.89E06	7.15E06	NCA
	1990	4.10E06	5.98E06	NCA
	2000	4.10E06	5.98E06	4.10E06
60.0	1980	1.14E07	NCA	NCA
	1985	9.81E06	1.43E07	NCA
	1990	8.32E06	1.20E07	NCA
	2000	8.32E06	1.20E07	NCA
100.0	1980	1.90E07	NCA	NCA
	1985	1.63E07	2.38E07	NCA
	1990	1.37E07	1.99E07	NCA
	2000	1.37E07	1.99E07	NCA
250.0	1980	NCA	NCA	NCA
	1985	4.08E07	5.95E07	NCA
	1990	3.41E07	4.98E07	NCA
	2000	3.41E07	4.98E07	NCA
500.0	1980	NCA	NCA	NCA
	1985	8.15E07	NCA	NCA
	1990	6.83E07	1.01E08	NCA
	2000	6.83E07	1.01E08	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.04E08	1.50E08	NCA
	2000	1.04E08	1.50E08	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.37E08	NCA	NCA
	2000	1.37E08	1.99E08	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	6.83E08	NCA	NCA

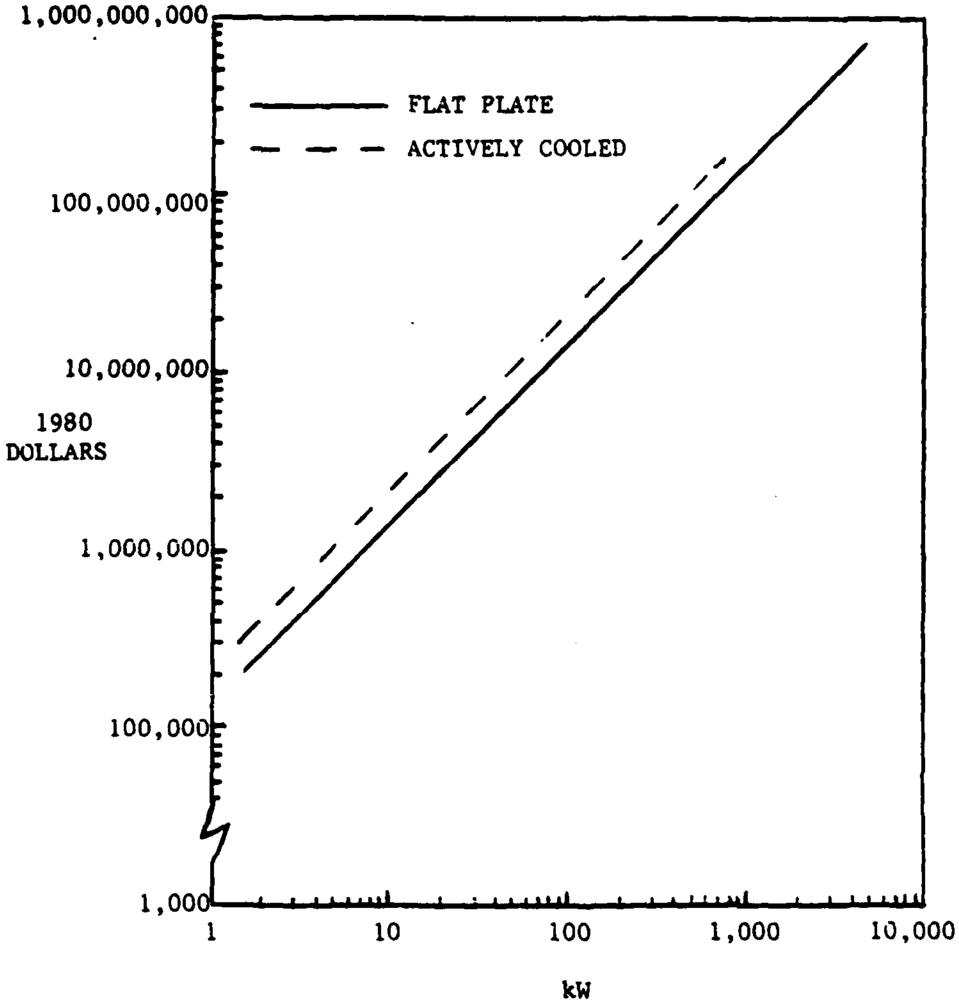

Figure 37. PHOTOVOLTAIC SYSTEM ACQUISITION COST

Annual Operations and Maintenance Cost. Photovoltaic "Annual Operations and Maintenance Cost" parameter values are in Table 49 and in Figure 38.

Table 49. PHOTOVOLTAIC ANNUAL OPERATIONS AND MAINTENANCE COST (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	FLAT PLATE	ACTIVELY COOLED	PHOTOCHEMICAL
1.5	1980	1.81E04	2.60E04	NCA
	1985	1.54E04	2.22E04	NCA
	1990	1.32E04	1.89E04	NCA
	2000	1.32E04	1.89E04	1.32E04
5.0	1980	6.05E04	8.66E04	NCA
	1985	5.14E04	7.39E04	NCA
	1990	4.40E04	6.31E04	NCA
	2000	4.40E04	6.31E04	4.40E04
20.0	1980	2.42E05	3.47E05	NCA
	1985	2.06E05	2.96E05	NCA
	1990	1.76E05	2.52E05	NCA
	2000	1.76E05	2.52E05	1.76E05
30.0	1980	3.63E05	5.21E05	NCA
	1985	3.08E05	4.44E05	NCA
	1990	2.61E05	3.74E05	NCA
	2000	2.61E05	3.74E05	2.61E05
60.0	1980	7.28E05	NCA	NCA
	1985	6.19E05	8.88E05	NCA
	1990	5.29E05	7.50E05	NCA
	2000	5.29E05	7.50E05	NCA
100.0	1980	1.21E06	NCA	NCA
	1985	1.03E06	1.48E06	NCA
	1990	8.72E05	1.24E06	NCA
	2000	8.72E05	1.24E06	NCA
250.0	1980	NCA	NCA	NCA
	1985	2.57E06	3.70E06	NCA
	1990	2.17E06	3.11E06	NCA
	2000	2.17E06	3.11E06	NCA
500.0	1980	NCA	NCA	NCA
	1985	5.14E06	NCA	NCA
	1990	4.35E06	6.31E06	NCA
	2000	4.35E06	6.31E06	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	6.62E06	9.38E06	NCA
	2000	6.62E06	9.38E06	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	8.72E06	NCA	NCA
	2000	8.72E06	1.24E07	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	4.35E07	NCA	NCA

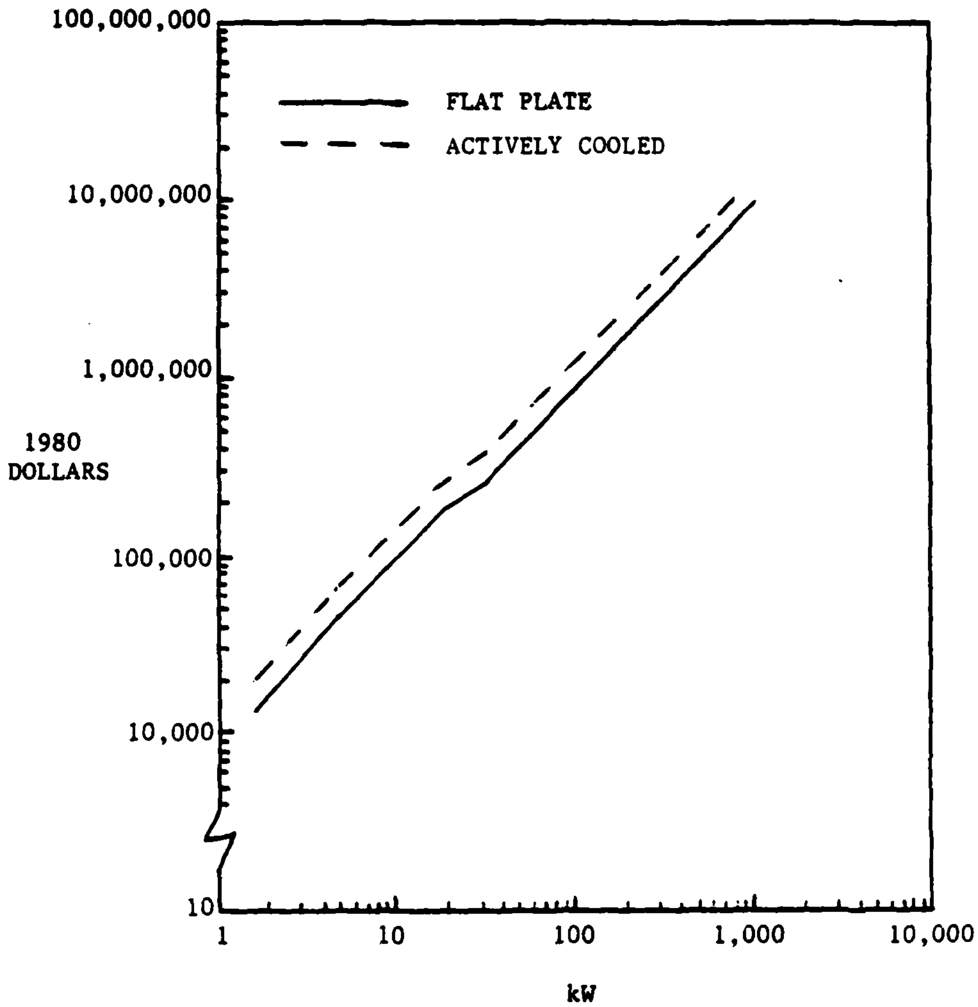

Figure 38. PHOTOVOLTAIC ANNUAL OPERATIONS AND MAINTENANCE COST

System Efficiency. Photovoltaic "System Efficiency" parameter values are presented in Table 50 and in Figure 39. Photovoltaic system efficiency is defined as —

[(Monthly average system energy output per square foot of array) ÷ (Monthly average insolation in plane of array)]

where insolation is for the month with the lowest insolation value.

Table 50. PHOTOVOLTAIC SYSTEM EFFICIENCY (%)

POWER OUTPUT LEVEL, KW	YEAR	FLAT PLATE	ACTIVELY COOLED	PHOTOCHEMICAL
1.5	1980	8.7	6.9	NCA
	1985	9.5	7.5	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	9.5
5.0	1980	8.7	6.9	NCA
	1985	9.5	7.5	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	9.5
20.0	1980	8.7	6.9	NCA
	1985	9.5	7.5	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	9.5
30.0	1980	8.7	6.9	NCA
	1985	9.5	7.5	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	9.5
60.0	1980	8.7	NCA	NCA
	1985	9.5	7.5	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	NCA
100.0	1980	8.7	NCA	NCA
	1985	9.5	7.5	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	NCA
250.0	1980	NCA	NCA	NCA
	1985	9.5	7.5	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	NCA
500.0	1980	NCA	NCA	NCA
	1985	9.5	NCA	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	11.4	9.0	NCA
	2000	13.3	10.5	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	11.4	NCA	NCA
	2000	13.3	10.5	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	13.3	NCA	NCA

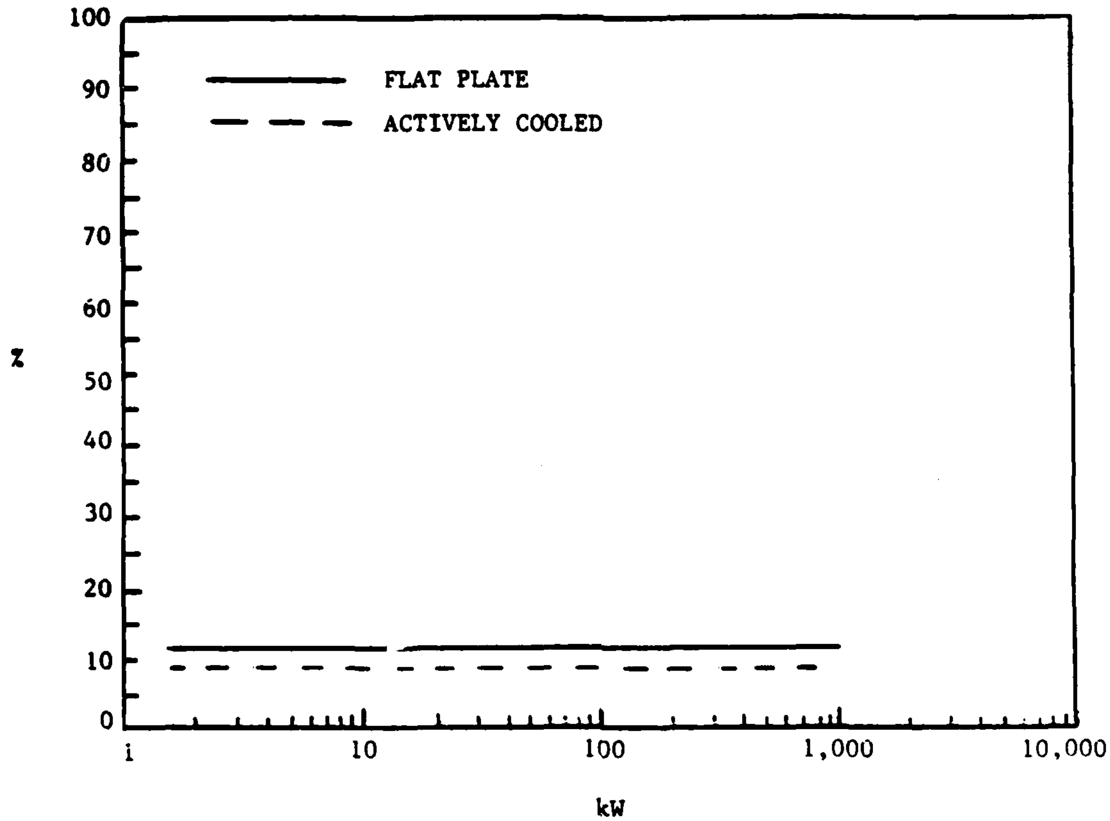

Figure 39. PHOTOVOLTAIC SYSTEM EFFICIENCY

Fuel Consumption. Because photovoltaic power systems use only sunlight as their "fuel" source, fuel consumption is zero for all system capacities.

Annual Fuel Cost. Annual fuel cost for photovoltaic power systems is zero dollars per year.

Life-Cycle Cost. Photovoltaic power system "Life-Cycle Cost" parameter values are presented in Table 51 and in Figure 40. Because fuel cost is zero, photovoltaic power systems are not sensitive to fuel cost escalation rates. Life-cycle costs are based on two replacements of the lead-acid battery storage subsystem during the 20 year economic analysis period and one replacement of the inverter. Replacement costs include installation at 25% of off-the-shelf equipment costs. The batteries and inverter installed when the photovoltaic power system is initially installed have an installation cost of 50% of the off-the-shelf equipment costs. Battery costs are based on lead-acid battery costs in the year in which system is installed.

Table 51. PHOTOVOLTAIC POWER SYSTEM LIFE CYCLE COST (1980 CENTS/kWh)

POWER OUTPUT LEVEL, KW	YEAR	FLAT PLATE	ACTIVELY COOLED	PHOTOCHEMICAL
1.5	1980	185.2	269.0	NCA
	1985	159.0	230.9	NCA
	1990	135.0	196.1	NCA
	2000	135.0	196.1	135.0
5.0	1980	185.6	268.5	NCA
	1985	158.9	230.7	NCA
	1990	135.3	196.2	NCA
	2000	135.3	196.2	135.0
20.0	1980	185.7	269.3	NCA
	1985	159.0	230.8	NCA
	1990	135.3	196.1	NCA
	2000	135.3	196.1	135.3
30.0	1980	185.6	269.4	NCA
	1985	158.6	231.1	NCA
	1990	[illegible]	[illegible]	NCA
	2000	[illegible]	193.7	[illegible]
50.0	1980	[illegible]	NCA	NCA
	1985	158.9	231.1	NCA
	1990	133.8	194.3	NCA
	2000	133.8	194.3	NCA
100.0	1980	185.8	NCA	NCA
	1985	159.0	230.8	NCA
	1990	134.0	193.2	NCA
	2000	134.0	193.2	NCA
250.0	1980	NCA	NCA	NCA
	1985	158.9	230.8	NCA
	1990	133.8	193.5	NCA
	2000	133.8	193.5	NCA
500.0	1980	NCA	NCA	NCA
	1985	158.9	NCA	NCA
	1990	133.6	196.2	NCA
	2000	133.6	196.2	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	134.0	194.4	NCA
	2000	134.0	194.4	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	134.0	NCA	NCA
	2000	134.0	193.2	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	133.6	NCA	NCA

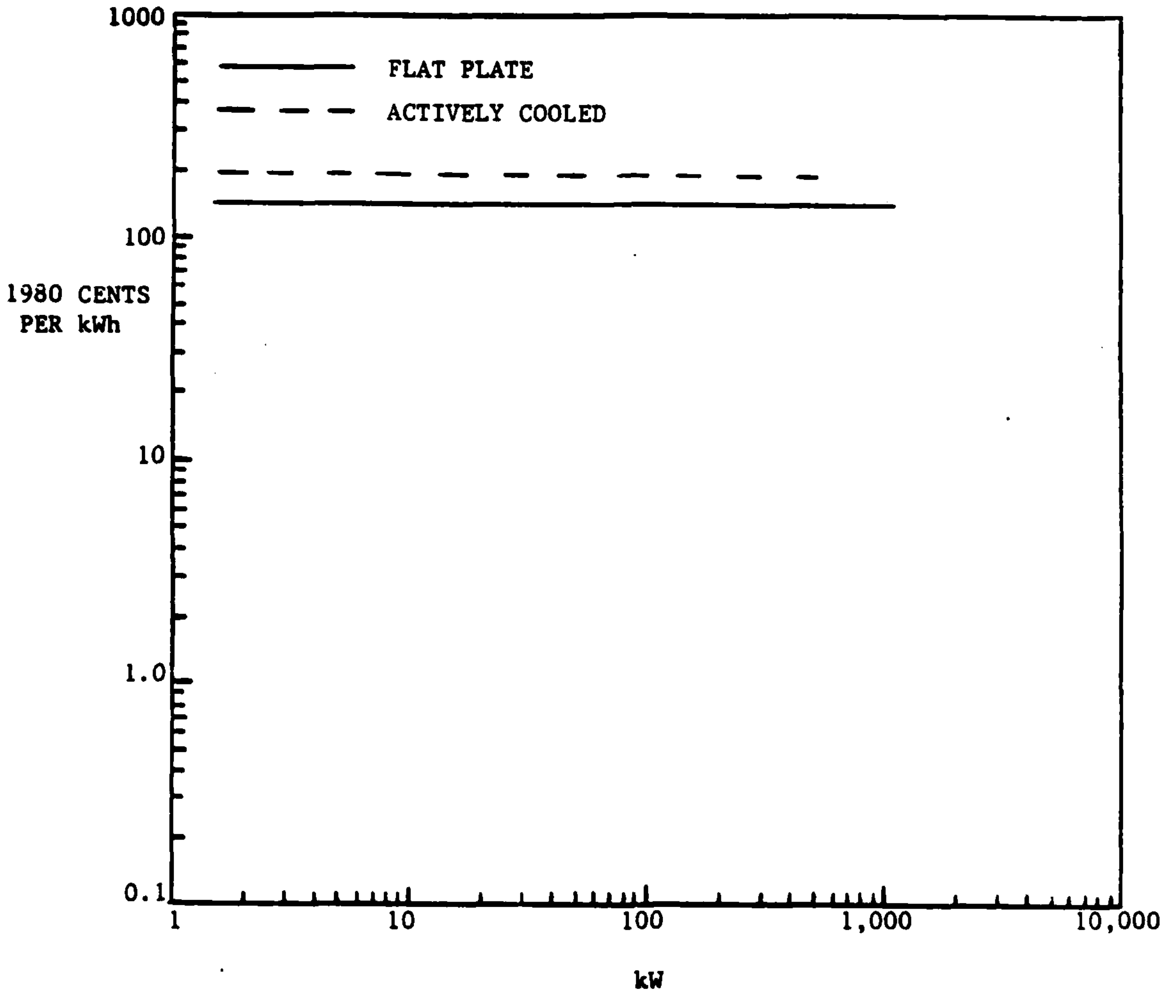

Figure 40. PHOTOVOLTAIC LIFE CYCLE COST

System Volume. Photovoltaic power "System Volume" parameter values are presented in Table 52.

Table 52. PHOTOVOLTAIC POWER SYSTEM VOLUME (Cubic Feet)

POWER OUTPUT LEVEL, KW	YEAR	FLAT PLATE	ACTIVELY COOLED	PHOTOCHEMICAL
1.5	1980	1.96E05	2.94E05	NCA
	1985	1.96E05	2.94E05	NCA
	1990	1.96E05	2.94E05	NCA
	2000	1.96E05	2.94E05	1.96E05
5.0	1980	6.53E05	9.80E05	NCA
	1985	6.53E05	9.80E05	NCA
	1990	6.53E05	9.80E05	NCA
	2000	6.53E05	9.80E05	6.53E05
20.0	1980	2.61E06	3.92E05	NCA
	1985	2.61E06	3.92E05	NCA
	1990	2.61E06	3.92E05	NCA
	2000	2.61E06	3.92E05	2.61E06
30.0	1980	3.92E06	5.88E06	NCA
	1985	3.92E06	5.88E06	NCA
	1990	3.92E06	5.88E06	NCA
	2000	3.92E06	5.88E06	3.92E06
60.0	1980	7.84E06	NCA	NCA
	1985	7.84E06	1.18E07	NCA
	1990	7.84E06	1.18E07	NCA
	2000	7.84E06	1.18E07	NCA
100.0	1980	1.31E07	NCA	NCA
	1985	1.31E07	1.96E07	NCA
	1990	1.31E07	1.96E07	NCA
	2000	1.31E07	1.96E07	NCA
250.0	1980	NCA	NCA	NCA
	1985	3.26E07	4.96E07	NCA
	1990	3.26E07	4.96E07	NCA
	2000	3.26E07	4.96E07	NCA
500.0	1980	NCA	NCA	NCA
	1985	6.53E07	NCA	NCA
	1990	6.53E07	9.80E07	NCA
	2000	6.53E07	9.80E07	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	9.79E07	1.47E08	NCA
	2000	9.79E07	1.47E08	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	1.31E08	NCA	NCA
	2000	1.31E08	1.96E08	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	6.53E08	NCA	NCA

System Weight. Photovoltaic power "System Weight" parameter values are presented in Table 53.

Table 53. PHOTOVOLTAIC POWER SYSTEM WEIGHT (POUNDS)

POWER OUTPUT LEVEL, KW	YEAR	FLAT PLATE	ACTIVELY COOLED	PHOTOCHEMICAL
1.5	1980	8.46E03	2.45E04	NCA
	1985	7.88E03	2.38E04	NCA
	1990	7.66E03	2.36E04	NCA
	2000	7.58E03	2.35E04	7.58E03
5.0	1980	2.82E04	8.16E04	NCA
	1985	2.63E04	7.93E04	NCA
	1990	2.55E04	7.87E04	NCA
	2000	2.53E04	7.83E04	2.53E04
20.0	1980	1.13E05	3.26E05	NCA
	1985	1.05E05	3.17E05	NCA
	1990	1.02E05	3.15E05	NCA
	2000	1.01E05	3.13E05	1.01E05
30.0	1980	1.68E05	4.89E05	NCA
	1985	1.57E05	4.76E05	NCA
	1990	1.53E05	4.73E05	NCA
	2000	1.52E05	4.70E05	1.52E05
60.0	1980	3.37E05	NCA	NCA
	1985	3.14E05	9.52E05	NCA
	1990	3.06E05	9.46E05	NCA
	2000	3.04E05	9.40E05	NCA
100.0	1980	5.61E05	NCA	NCA
	1985	5.25E05	1.59E06	NCA
	1990	5.10E05	1.58E06	NCA
	2000	5.05E05	1.57E06	NCA
250.0	1980	NCA	NCA	NCA
	1985	1.31E06	3.98E06	NCA
	1990	1.28E06	3.95E06	NCA
	2000	1.26E06	3.93E06	NCA
500.0	1980	NCA	NCA	NCA
	1985	2.62E06	NCA	NCA
	1990	2.54E06	7.90E06	NCA
	2000	2.52E05	7.86E06	NCA
750.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	3.84E06	1.18E07	NCA
	2000	3.78E06	1.18E07	NCA
1000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	5.10E06	NCA	NCA
	2000	5.05E06	1.57E07	NCA
5000.0	1980	NCA	NCA	NCA
	1985	NCA	NCA	NCA
	1990	NCA	NCA	NCA
	2000	2.52E07	NCA	NCA

Fuel Requirements and Capabilities. Photovoltaic power systems use no fuel. They are "fueled" by sunlight. In sunny areas system size may be reduced, and system life-cycle cost correspondingly reduced. In areas with little sun, system size may have to be increased to insure acceptable performance, and system life-cycle costs will be increased.

Start-up Time. Photovoltaic power system "Start-up Time" is 5 minutes and assumes motor starting loads are present. In cases where minimal motor starting loads are present, start-up times will be less than 5 minutes.

Shutdown Time. Photovoltaic power system "Shutdown Time" is one minute.

Reliability. Photovoltaic power system "Reliability" has an ordinal score of 3 indicating average reliability. Photovoltaic power systems have comparable reliability to diesels. Solar availability strongly influences system reliability.

Environmental Constraints. Photovoltaic power systems have an ordinal score of 5 for "Environmental Constraints" indicating minimum potential environmental constraints. Photovoltaic power systems have less environmental constraints than diesels.

Location Constraints. Photovoltaic power systems have an ordinal score of 3 indicating average location constraints. Photovoltaic power systems have a comparable locational constraint rating to diesels. Systems will not perform well at high latitudes with short winter days.

Operation Constraints. Photovoltaic power systems have an ordinal score of 2 indicating poor turn-down capability with large efficiency penalty. Diesels have better operational constraints. Photovoltaic systems have no overload capability.

Wind Turbines

There are two types of wind turbines of interest in this study: horizontal axis and vertical axis. The only real difference between the two is the orientation of the turbine shaft and, therefore, vertical-axis wind turbines do not have to track the wind direction. The system configuration is presented in Figure 41. Because of the general requirement for continuous AC power output, wind systems include battery storage.

Because the wind systems are dependent upon a number of locational factors (the distribution of wind speed) and machine design factors (cut-in speed and rated wind speed), a continuous AC power output system of 10 kW requires a wind turbine with a rated capacity of greater than 10 kW. To appropriately identify the required wind turbine rated capacity for the system output requirements, capacity factors were calculated.

The capacity factor (CF) of the wind turbine is the ratio of the average wind turbine energy output in a specific wind speed regime to the rated energy output as if wind speed is always at the speed at which the wind turbine is rated. The capacity factor is dependent on the following parameters:

SI $\equiv$ Cut-in speed of the wind machine defined as the wind speed at which the wind machine begins to produce useful power

SR $\equiv$ Rated wind speed defined as the wind speed at which the wind machine produces its rated power output

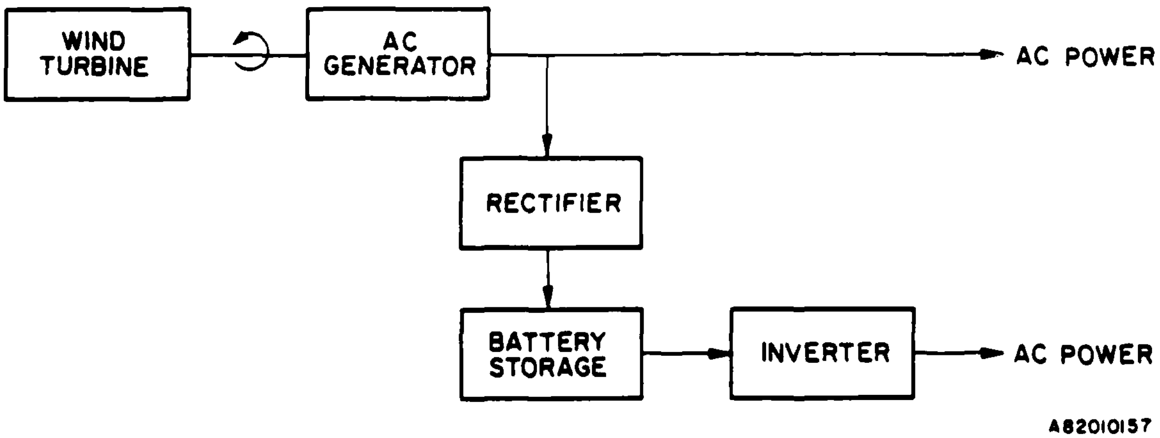

Figure 41. WIND TURBINE SYSTEMS

SA ≡ The time weighted average of the wind speed during a month at the site. This procedure assumes that wind follows a Rayleigh distribution with parameters "g" = 1 and "c" = 2. The mean wind speed for system design should be for the worst month of the year at the site under consideration to ensure that the system will meet the general requirements of continuous power output.

To determine the capacity factors for the wind turbines, the cut-in speed (SI) and the rated wind speed (SR) were obtained from the literature search and the surveys on the wind systems. The mean wind speed (SA) is assumed to be 8.1 mph, which is the mean (standard deviation of 1.7 mph) of monthly mean wind speeds for 70 nationwide sites for the month of August. August generally has the lowest mean wind speeds.

Given the capacity factor of the wind machine, the rated capacity of the wind machine at continuous power output levels can be calculated with the following assumptions:

1) η_b is assumed at 79%

2) η_I is assumed at 90%

3) One day's electrical energy storage is assumed for 80% depth of discharge of batteries regardless of mean wind speed. Thus, a 10-kW continuous system requires 240 kWh of storage or 300 kWh of batteries.

4) x = 0.5; 50% of the wind machine output goes directly to load, and 50% goes to storage and then to load.

With a value of SA of 8.1 mph, the rated capacity of the wind turbine is 15.54 times its continuous power output rating (a wind turbine for 100 kW continuous power output is rated at 1,554 kW).

Note that the capacity factor (CF) is quite sensitive to the mean wind speed. For example, cases assuming a cut-in wind speed of 7.5 mph and a rated wind speed of 23.0 mph and four mean wind speeds of 8.1, 10, 12, and 15 mph were calculated (tabulated below). Consequently, the parameter values estimated for the wind systems are likely to be overestimated if the mean wind speed is greater than 8.1 mph and underestimated if the mean wind speed is less than 8.1 mph.

Mean Wind Speed, mph	Rated Capacity of Wind Machine Required for 10 kW Continuous, kW
8.1	155
10	69
12	44
15	29

Technology Status. Vertical axis wind turbines are currently available in capacities of 1.5 to 5.0 kW. In 1985 they are expected to be available in capacities through 30.0 kW. In 1990 they are expected to be available in capacities through 60.0 kW. In 2000 they are expected to be available in capacities through 100.0 kW.

Horizontal axis wind turbines are currently available in capacities of 1.5 to 250.0 kW. In 1985 they will be available in capacities through 750.0 kW. In 1990 they will be available in capacities through 1000.0 kW.

The primary reasons for the lag in the availability of larger capacity machines is the lack of an extensive market which would be required to minimize the manufacturing costs.

Type. Wind turbine systems "Type" parameter values are presented in Table 54. All wind turbine systems are fixed.

System Acquisition Cost. Wind turbine "System Acquisition Cost" parameter values are presented in Table 55 and in Figure 42.

Table 54. WIND TURBINE SYSTEM TYPE (Fixed)

POWER OUTPUT LEVEL, KW	YEAR	VERTICAL AXIS	HORIZONTAL AXIS
1.5	1980	F	F
	1985	F	F
	1990	F	F
	2000	F	F
5.0	1980	F	F
	1985	F	F
	1990	F	F
	2000	F	F
20.0	1980	NCA	F
	1985	F	F
	1990	F	F
	2000	F	F
30.0	1980	NCA	F
	1985	F	F
	1990	F	F
	2000	F	F
60.0	1980	NCA	F
	1985	NCA	F
	1990	F	F
	2000	F	F
100.0	1980	NCA	F
	1985	NCA	F
	1990	NCA	F
	2000	F	F
250.0	1980	NCA	F
	1985	NCA	F
	1990	NCA	F
	2000	NCA	F
500.0	1980	NCA	NCA
	1985	NCA	F
	1990	NCA	F
	2000	NCA	F
750.0	1980	NCA	NCA
	1985	NCA	F
	1990	NCA	F
	2000	NCA	F
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	F
	2000	NCA	F
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

Table 55. WIND TURBINE SYSTEM ACQUISITION COST (1980 dollars)

POWER OUTPUT LEVEL, KW	YEAR	VERTICAL AXIS	HORIZONTAL AXIS
1.5	1980	3.54E04	3.54E04
	1985	3.36E04	3.36E04
	1990	3.17E04	3.17E04
	2000	3.17E04	3.17E04
5.0	1980	7.41E04	7.41E04
	1985	7.04E04	7.04E04
	1990	6.67E04	6.67E04
	2000	6.67E04	6.67E04
20.0	1980	NCA	2.00E05
	1985	1.90E05	1.90E05
	1990	1.80E05	1.80E05
	2000	1.80E05	1.80E05
30.0	1980	NCA	2.75E05
	1985	2.61E05	2.61E05
	1990	2.48E05	2.48E05
	2000	2.48E05	2.48E05
60.0	1980	NCA	4.86E05
	1985	NCA	4.62E05
	1990	4.37E05	4.37E05
	2000	4.37E05	4.37E05
100.0	1980	NCA	7.55E05
	1985	NCA	7.17E05
	1990	NCA	6.49E05
	2000	6.49E05	6.49E05
250.0	1980	NCA	1.72E06
	1985	NCA	1.63E06
	1990	NCA	1.55E06
	2000	NCA	1.55E06
500.0	1980	NCA	NCA
	1985	NCA	3.26E06
	1990	NCA	3.10E06
	2000	NCA	3.10E06
750.0	1980	NCA	NCA
	1985	NCA	4.89E06
	1990	NCA	4.65E06
	2000	NCA	4.65E06
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	6.20E06
	2000	NCA	6.20E06
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

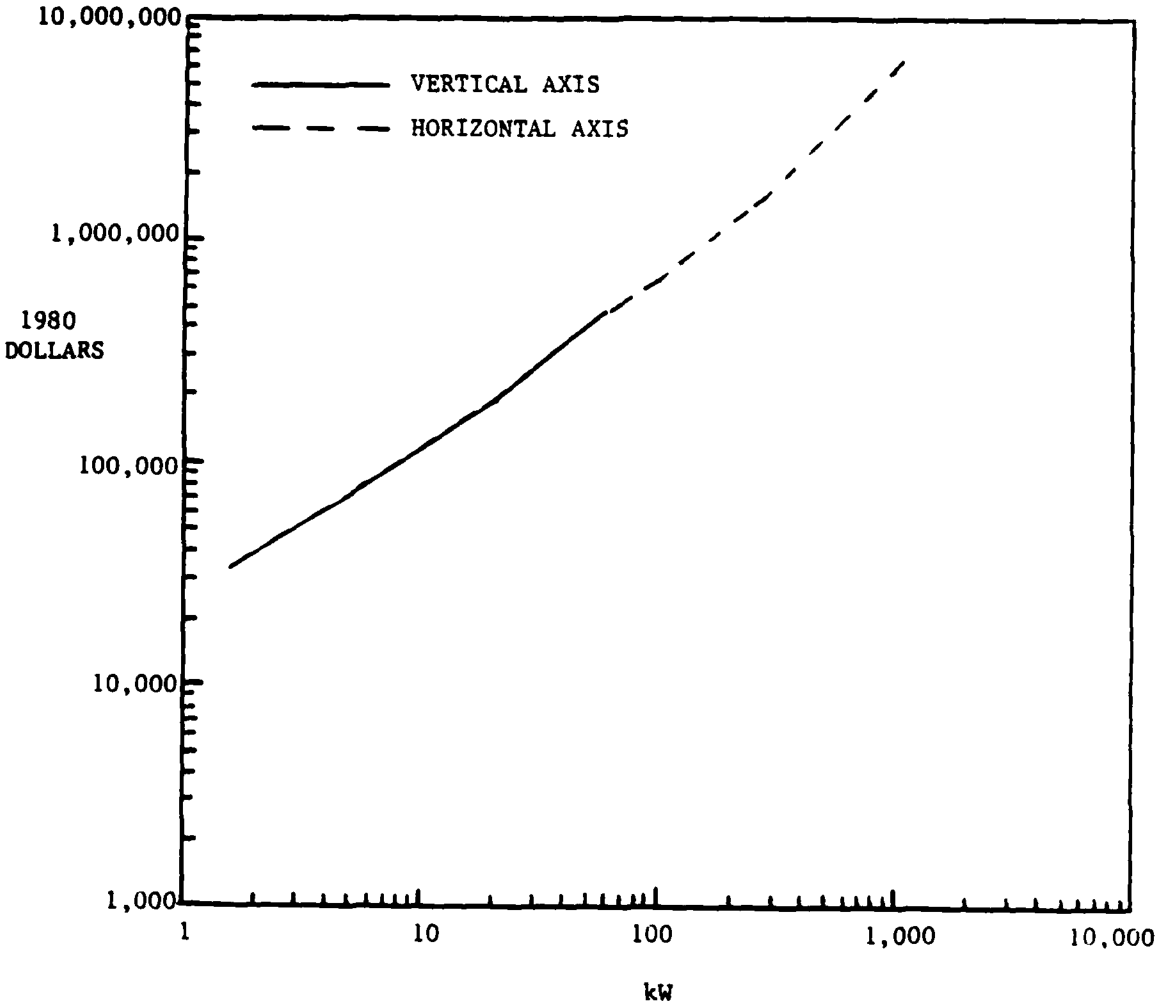

Figure 42. WIND TURBINE SYSTEM ACQUISITION COST

Annual Operations and Maintenance Cost. Wind turbine "Annual Operations and Maintenance Cost" parameter values are presented in Table 56 and in Figure 43.

Table 56. WIND TURBINE ANNUAL OPERATIONS AND MAINTENANCE COSTS (1980 DOLLARS)

POWER OUTPUT LEVEL, KW	YEAR	VERTICAL AXIS	HORIZONTAL AXIS
1.5	1980	1.81E03	1.81E03
	1985	1.42E03	1.42E03
	1990	1.38E03	1.38E03
	2000	1.38E03	1.38E03
5.0	1980	5.15E03	5.15E03
	1985	3.91E03	3.91E03
	1990	3.83E03	3.83E03
	2000	3.83E03	3.83E03
20.0	1980	NCA	1.87E04
	1985	1.38E04	1.38E04
	1990	1.36E04	1.36E04
	2000	1.36E04	1.36E04
30.0	1980	NCA	2.76E04
	1985	2.02E04	2.02E04
	1990	1.99E04	1.99E04
	2000	1.99E04	1.99E04
60.0	1980	NCA	5.38E04
	1985	NCA	3.94E04
	1990	3.88E04	3.88E04
	2000	3.88E04	3.88E04
100.0	1980	NCA	8.86E04
	1985	NCA	6.48E04
	1990	NCA	6.29E04
	2000	6.29E04	6.29E04
250.0	1980	NCA	2.18E05
	1985	NCA	1.60E05
	1990	NCA	1.56E05
	2000	NCA	1.56E05
500.0	1980	NCA	NCA
	1985	NCA	3.19E05
	1990	NCA	3.11E05
	2000	NCA	3.11E05
750.0	1980	NCA	NCA
	1985	NCA	4.79E05
	1990	NCA	4.67E05
	2000	NCA	4.67E05
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	6.23E05
	2000	NCA	6.23E05
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

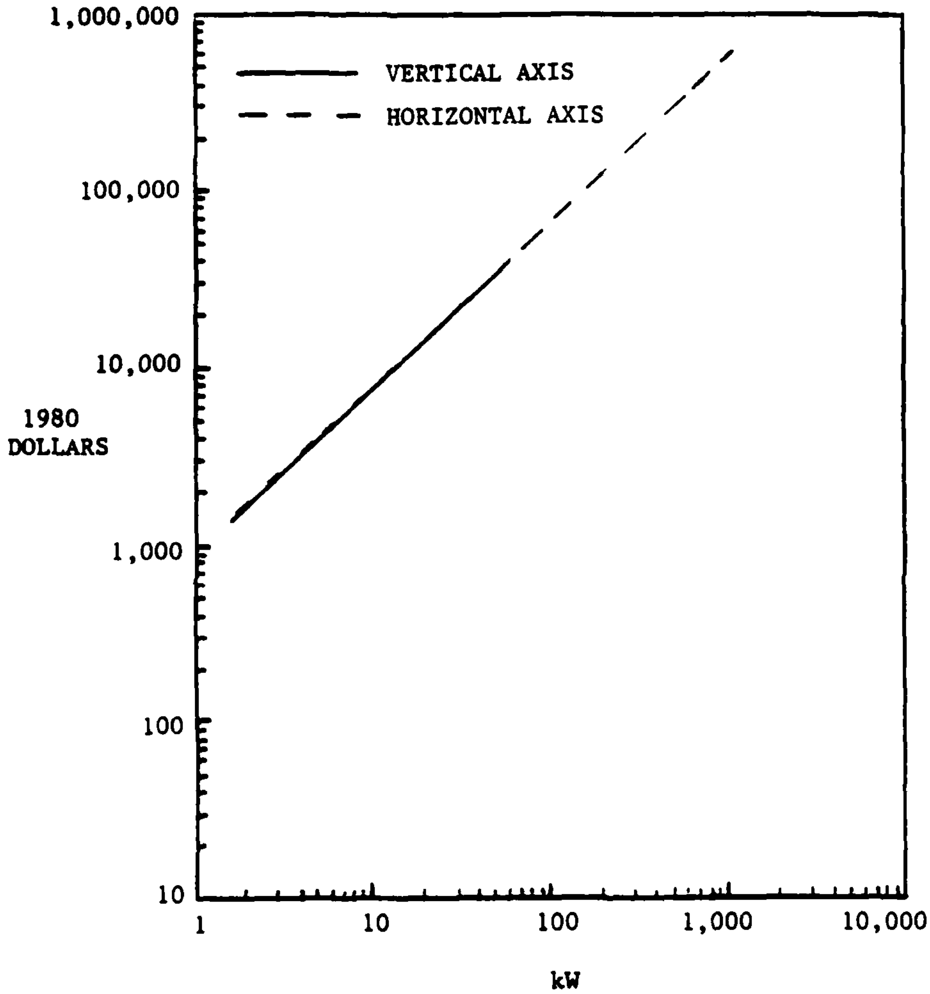

Figure 43. WIND TURBINE ANNUAL OPERATIONS AND MAINTENANCE COST

System Efficiency. Wind turbine "System Efficiency" parameter values are presented in Table 57 and in Figure 44. Wind turbine system efficiency is defined as —

(Actual system continuous output at mean wind speed of 8.1 mph) ÷ (Power in wind at 8.1 mph mean wind speed)

where the power in wind takes into account the wind speed distribution.

Table 57. WIND TURBINE SYSTEM EFFICIENCY (%)

POWER OUTPUT LEVEL, KW	YEAR	VERTICAL AXIS	HORIZONTAL AXIS
1.5	1980	26.5	26.9
	1985	26.5	26.9
	1990	26.5	26.9
	2000	26.5	26.9
5.0	1980	29.9	31.1
	1985	29.9	31.1
	1990	29.9	31.1
	2000	29.9	31.1
20.0	1980	NCA	36.7
	1985	36.4	36.7
	1990	36.4	36.7
	2000	36.4	36.7
30.0	1980	NCA	38.5
	1985	38.1	38.5
	1990	38.1	38.5
	2000	38.1	38.5
60.0	1980	NCA	41.8
	1985	NCA	41.8
	1990	41.3	41.8
	2000	41.3	41.8
100.0	1980	NCA	44.4
	1985	NCA	44.4
	1990	NCA	44.4
	2000	43.9	44.4
250.0	1980	NCA	49.6
	1985	NCA	49.6
	1990	NCA	49.6
	2000	NCA	49.6
500.0	1980	NCA	NCA
	1985	NCA	49.6
	1990	NCA	49.6
	2000	NCA	49.6
750.0	1980	NCA	NCA
	1985	NCA	49.6
	1990	NCA	49.6
	2000	NCA	49.6
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	49.6
	2000	NCA	49.6
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

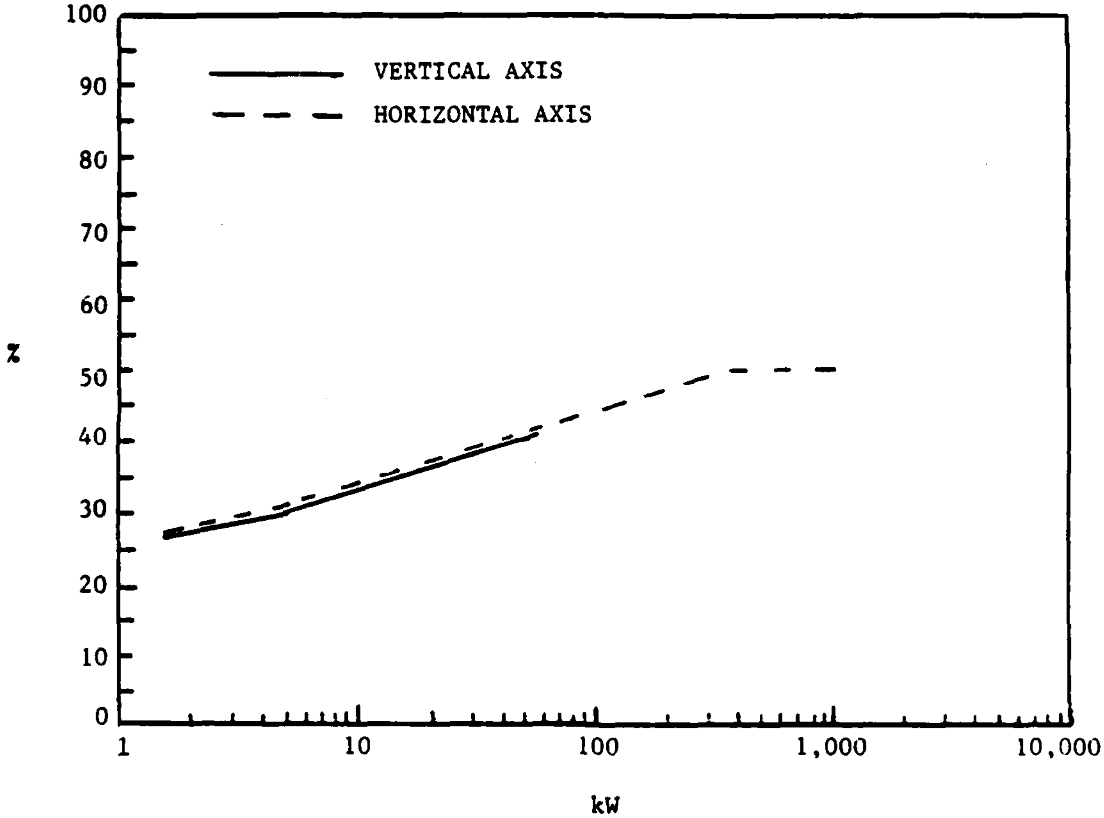

Figure 44. WIND TURBINE SYSTEM EFFICIENCY

Fuel Consumption. Because wind turbine systems use only the wind as their "fuel" source, fuel consumption is zero for all system capacities.

Annual Fuel Cost. Annual fuel cost for wind turbine systems is zero dollars per year.

Life-Cycle Cost. Wind turbine "Life-Cycle Cost" parameter values are presented in Table 58 and in Figure 45. Because fuel cost is zero, wind turbines are not sensitive to fuel cost escalation rates. Life-cycle costs are based on two replacements of the lead-acid battery storage subsystem during the 20 year economic analysis period and one replacement of the inverter. Replacement costs include installation at 25% of off-the-shelf equipment costs. The batteries and inverter installed when the wind turbine system is initially installed have an installation cost of 50% of off-the-shelf equipment costs. Battery costs are based on lead-acid battery costs in the year in which system is installed.

Table 58. WIND TURBINE LIFE CYCLE COST
(1980 CENTS/kWh)

POWER OUTPUT LEVEL, KW	YEAR	VERTICAL AXIS	HORIZONTAL AXIS
1.5	1980	21.5	21.5
	1985	19.3	19.3
	1990	18.4	18.4
	2000	18.4	18.4
5.0	1980	15.0	15.0
	1985	13.2	13.2
	1990	12.6	12.6
	2000	12.6	12.6
20.0	1980	NCA	11.4
	1985	9.75	9.75
	1990	9.38	9.38
	2000	9.38	9.38
30.0	1980	NCA	10.8
	1985	9.15	9.15
	1990	8.82	8.82
	2000	8.82	8.82
60.0	1980	NCA	9.98
	1985	NCA	8.43
	1990	8.11	8.11
	2000	8.11	8.11
100.0	1980	NCA	9.57
	1985	NCA	8.05
	1990	NCA	7.51
	2000	7.52	7.51
250.0	1980	NCA	9.07
	1985	NCA	7.59
	1990	NCA	7.30
	2000	NCA	7.30
500.0	1980	NCA	NCA
	1985	NCA	7.58
	1990	NCA	7.29
	2000	NCA	7.29
750.0	1980	NCA	NCA
	1985	NCA	7.58
	1990	NCA	7.29
	2000	NCA	7.29
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	7.29
	2000	NCA	7.29
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

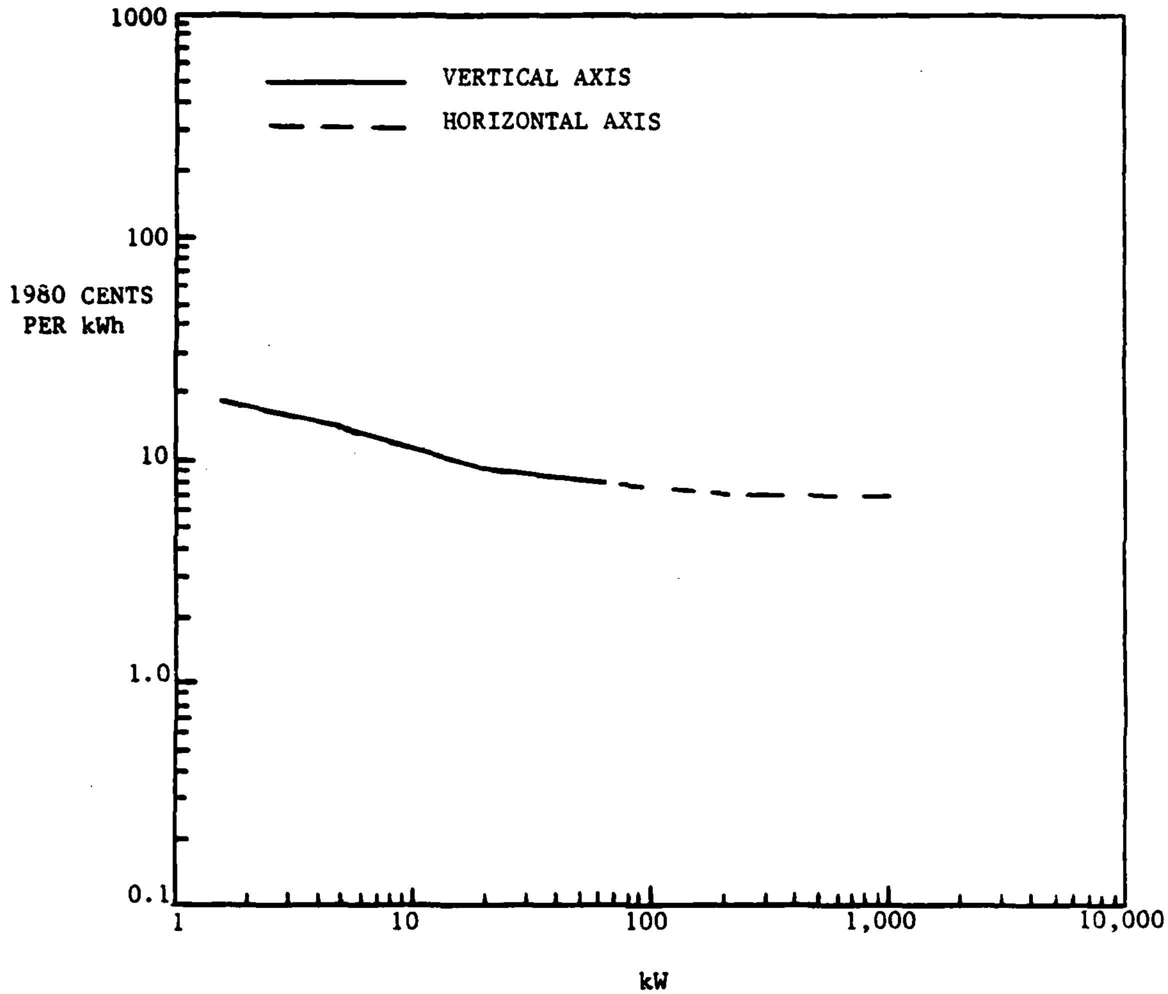

Figure 45. WIND TURBINE LIFE-CYCLE COST

System Volume. Wind turbine "System Volume" parameter values are presented in Table 59.

Table 59. WIND TURBINE SYSTEM VOLUME (CUBIC FEET)

POWER OUTPUT LEVEL, KW	YEAR	VERTICAL AXIS	HORIZONTAL AXIS
1.5	1980	1.98E02	3.96E02
	1985	1.98E02	3.96E02
	1990	1.98E02	3.96E02
	2000	1.98E02	3.96E02
5.0	1980	7.00E02	1.40E03
	1985	7.00E02	1.40E03
	1990	7.00E02	1.40E03
	2000	7.00E02	1.40E03
20.0	1980	NCA	1.03E04
	1985	5.15E02	1.03E04
	1990	5.15E02	1.03E04
	2000	5.15E02	1.03E04
30.0	1980	NCA	1.85E04
	1985	9.26E02	1.85E04
	1990	9.26E02	1.85E04
	2000	9.26E02	1.85E04
60.0	1980	NCA	5.02E04
	1985	NCA	5.02E04
	1990	2.51E03	5.02E04
	2000	2.51E03	5.02E04
100.0	1980	NCA	1.04E05
	1985	NCA	1.04E05
	1990	NCA	1.04E05
	2000	5.02E04	1.04E05
250.0	1980	NCA	3.88E05
	1985	NCA	3.88E05
	1990	NCA	3.88E05
	2000	NCA	3.88E05
500.0	1980	NCA	NCA
	1985	NCA	7.76E05
	1990	NCA	7.76E05
	2000	NCA	7.76E05
750.0	1980	NCA	NCA
	1985	NCA	1.16E06
	1990	NCA	1.16E06
	2000	NCA	1.16E06
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	1.04E06
	2000	NCA	1.04E06
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

System Weight. Wind turbine "System Weight" parameter values are presented in Table 60. Values for system sizes above 750 kW should be used with caution because of large variation in data in this range.

Table 60. WIND TURBINE SYSTEM WEIGHT (POUNDS)

POWER OUTPUT LEVEL, KW	YEAR	VERTICAL AXIS	HORIZONTAL AXIS
1.5	1980	9.53E03	9.53E03
	1985	8.79E03	8.79E03
	1990	8.50E03	8.50E03
	2000	8.40E03	8.40E03
5.0	1980	2.95E04	2.95E04
	1985	2.72E04	2.72E04
	1990	2.63E04	2.63E04
	2000	2.60E04	2.60E04
20.0	1980	NCA	9.88E04
	1985	9.11E04	9.11E04
	1990	8.81E04	8.81E04
	2000	8.71E04	8.71E04
30.0	1980	NCA	1.42E05
	1985	1.31E05	1.31E05
	1990	1.27E05	1.27E05
	2000	1.26E05	1.26E05
60.0	1980	NCA	2.68E05
	1985	NCA	2.47E05
	1990	2.39E05	2.39E05
	2000	2.36E05	2.36E05
100.0	1980	NCA	4.29E05
	1985	NCA	3.95E05
	1990	NCA	3.82E05
	2000	3.78E05	3.78E05
250.0	1980	NCA	1.01E06
	1985	NCA	9.31E05
	1990	NCA	9.00E05
	2000	NCA	8.90E05
500.0	1980	NCA	NCA
	1985	NCA	1.86E06
	1990	NCA	1.80E06
	2000	NCA	1.78E06
750.0	1980	NCA	NCA
	1985	NCA	2.79E06
	1990	NCA	2.70E06
	2000	NCA	2.67E06
1000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	3.82E06
	2000	NCA	3.78E06
5000.0	1980	NCA	NCA
	1985	NCA	NCA
	1990	NCA	NCA
	2000	NCA	NCA

Fuel Requirements and Capabilities. Wind turbine systems use no fuel; they are "fueled" by wind. In areas of high average wind speeds, system size may be reduced, and system life-cycle cost correspondingly reduced. In areas with low average wind speeds, system size may have to be increased to ensure acceptable performance and system life-cycle costs will be increased.

Start-up Time. Wind turbine start-up time is estimated at 10 seconds at 1.5 and 5.0 kW capacities, 1 minute at 20.0 and 30.0 kW capacities, 2 minutes at 60.0 and 100.0 kW capacities, and 5.0 minutes for capacities of 250.0 kW or more.

Shutdown Time. Wind turbine shutdown time is estimated at 10 seconds at 1.5 and 5.0 kW capacities, 1 minute at 20.0 and 30.0 kW capacities, 2 minutes at 60.0 and 100.0 kW capacities, and 5 minutes for capacities of 250.0 kW or more.

Reliability. Wind turbines have an ordinal score of 2 indicating moderate potential unreliability. Wind turbines are less reliable than diesels because turbines have moving parts with large mass and experience high stresses at high wind speeds.

Environmental Constraints. Wind turbines have an ordinal score of 5, indicating minimum potential environmental constraints. Wind turbines have less environmental constraints than diesels. Wind turbines may generate objectional low-frequency tones.

Location Constraints. Wind turbines have an ordinal score of 3 indicating average locational constraints. Wind turbines have a comparable locational constraint rating to diesels. Wind availability is the major constraint.

Operation Constraints. Wind turbines have an ordinal score of 2 indicating poor turn-down capability with large efficiency penalty. Diesels have better operational constraints. Wind turbines have no overload capability.

Batteries

There are seven types of batteries of interest in this study, although none affect the conceptual system configuration: Zn/Cl_2 (zinc-chlorine), Zn/Br_2 (zinc-bromine), Ni/Fe (nickel-iron), $Li\text{-}Al/FeS_2$ (lithium-aluminum/iron sulfide), Na/S (sodium/sulfur), Advanced Sealed Lead Acid, Redox Cr-Fe. As shown, Figure 46, the system consists of a charger and the battery. However, the charger is shown only because the cost of AC power into the battery (as DC power) must be adjusted for the efficiency of the charger. The efficiency of the charger has been assumed at 90%.

The basis of parameter values is delivered capacity, rather than rated capacity, after battery allowable depth of discharge is accounted for. Most batteries may only be discharged to a fraction of their rated capacity if acceptable long-term performance and life is to be obtained. Allowable depth of discharge is 80% of rated capacity for Ni/Fe, $Li\text{-}Al/FeS_2$, lead acid, and Na/S. Allowable depth of discharge is 100% of rated capacity for Zn/Cl_2, Zn/Br_2, and redox.

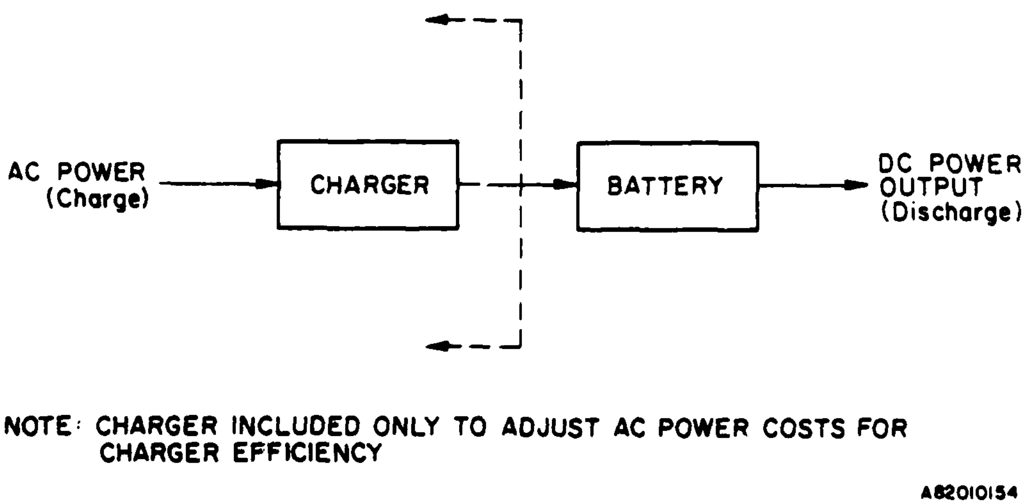

Figure 46. BATTERY SYSTEMS

Technology Status. Zn/Cl_2 batteries are expected to be commercially available in 1990. Zn/Br_2 batteries are expected to be commercially available in 1990. Ni/Fe batteries are expected to be commercially available in 1985. Na/S batteries are expected to be commercially available in 1990. Lead acid batteries are commercially available. Redox batteries are expected to be commercially available in 1990. Current research is focused on reducing the volume and weight of batteries while increasing efficiency and lifetime.

Type. Battery "Type" parameter values are presented in Table 61. Values are based only on a battery system with a capacity per charge/discharge cycle of one kWhr.

Table 61. BATTERY TYPE

PARAMETER: TYPE

UNITS: Mobile (M) /Transportable (T)/ Fixed (F) (at 1 kWhr capacity)

YEAR	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li\text{-}Al/FeS_2$	Na/S	Lead Acid	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	M	NCA
1985	NCA	NCA	M	M	NCA	M	NCA
1990	M	M	M	M	M	M	M
2000	M	M	M	M	M	M	M

System Acquisition Cost. Battery "System Acquisition Cost" parameter values are presented in Table 62. Values are based on a battery system with a capacity per charge/discharge cycle of 1 kWhr.

Table 62. BATTERY SYSTEM ACQUISITION COST

PARAMETER: System Acquisition Cost

UNITS: 1980 Dollars/ kWhr capacity

Year of Value	BATTERIES						
	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li\text{-}Al/FeS_2$	Na/S	Lead Acids	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	1.83E02	NCA
1985	NCA	NCA	1.35E02	9.76E01	NCA	1.24E02	NCA
1990	9.60E01	6.56E01	1.35E02	9.76E01	8.66E01	1.18E02	7.58E01
2000	8.66E01	6.24E01	1.29E02	9.26E01	8.26E01	1.18E02	7.20E01

Annual Operations and Maintenance Cost. Battery "Annual Operations and Maintenance Cost" parameter values are presented in Table 63. Operations and Maintenance cost is taken as 2% of system acquisition cost. Operations and maintenance cost values are based on a battery system with a capacity per charge/discharge cycle of 1 kWhr. Values are based on battery system duty of 2 charge/ discharge cycles per day. Less frequent cycling may result in reduced operations and maintenance costs.

Table 63. BATTERY ANNUAL OPERATIONS AND MAINTENANCE COST

PARAMETER: Annual Operations and Maintenance Cost

UNITS: 1980 Dollars/Year per kWhr capacity

Year of Value	BATTERIES						
	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li-Al/FeS_2$	Na/S	Lead Acid	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	3.66	NCA
1985	NCA	NCA	2.70	1.95	NCA	2.48	NCA
1990	1.92	1.31	2.70	1.95	1.73	2.36	1.52
2000	1.73	1.25	2.58	1.85	1.65	2.36	1.44

System Efficiency. Battery "System Efficiency" parameter values are presented in Table 64. System efficiency is based on system energy output divided by system energy input for a complete charge/discharge cycle.

Table 64. BATTERY SYSTEM EFFICIENCY

PARAMETER: EFFICIENCY UNITS: PER CENT

YEAR	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li-Al/FeS_2$	Na/S	Lead Acid	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	79.0	NCA
1985	NCA	NCA	65.0	75.0	NCA	82.0	NCA
1990	79.4	71.8	65.0	75.0	82.5	82.0	75.0
2000	83.4	75.4	68.3	82.0	84.0	83.0	78.8

Annual Electricity Required for Charging. Parameter values are presented in Table 65. Parameter values are based on a system that delivers one kWhr to load per charge/discharge cycle, 2 cycles per day, and a 90% availability of the system.

Table 65. ANNUAL ELECTRICITY REQUIRED FOR CHARGING BATTERIES

PARAMETER: Annual Electricity Required for Charging

UNITS: kWhr

Year of Value	BATTERIES						
	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li\text{-}Al/FeS_2$	Na/S	Lead Acid	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	1.03E03	NCA
1985	NCA	NCA	1.25E03	1.08E03	NCA	9.89E02	NCA
1990	1.02E+03	1.13E03	1.25E03	1.08E03	9.83E02	9.89E02	1.08E03
2000	9.73E+02	1.08E03	1.19E03	9.89E02	9.66E02	9.77E02	1.03E03

Annual Cost of Electricity for Charging. Parameter values for electricity cost based on 1980 dollars and no real escalation are presented in Table 66. Parameter values are based on a system that delivers one kWhr to load per charge/discharge cycle, 2 cycles per day, and a 90% availability of the system.

Table 66. ANNUAL COST OF ELECTRICITY FOR CHARGING BATTERIES, 0% FUEL ESCALATION

PARAMETER: Annual Cost of Electricity Required for Charging

UNITS: 1980 Dollars

Year of Value	BATTERIES						
	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li\text{-}Al/FeS_2$	Na/S	Lead Acid	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	1.62E01	NCA
1985	NCA	NCA	3.48E01	3.02E01	NCA	2.76E01	NCA
1990	2.85E01	3.15E01	3.48E01	3.02E01	2.74E01	2.76E01	3.02E01
2000	2.71E01	3.00E01	3.31E01	2.76E01	2.69E01	2.73E01	2.87E+01

Life-Cycle Cost. Parameter values are based on a 20-year system lifetime, 2 charge/discharge cycles per day, replacements of batteries when they have reached the end of their cycle lifetime, and 90% availability of the system. Life-cycle costs are in Table 67.

Table 67. BATTERY LIFE CYCLE COST

PARAMETER: Life-Cycle Cost

UNITS: 1980 $ per kWhr

Year of Value	BATTERIES						
	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li\text{-}Al/FeS_2$	Na/S	Lead Acid	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	1.80E-01	NCA
1985	NCA	NCA	6.39E-02	6.70E-02	NCA	8.48E-02	NCA
1990	4.25E-02	3.64E-02	5.98E-02	4.62E-02	4.49E-02	7.89E-02	2.59E-02
2000	3.92E-02	3.46E-02	5.65E-02	3.66E-02	3.57E-02	7.59E-02	2.46E-02

System Volume. Parameter values are based on a system capacity of 1 kWhr per charge/discharge cycle. Parameter values are presented in Table 68.

Table 68. BATTERY SYSTEM VOLUME

PARAMETER: Volume

UNITS: Cubic feet/kWhr capacity

Year of Value	BATTERIES						
	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li\text{-}Al/FeS_2$	Na/S	Lead Acid	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	9.10	NCA
1985	NCA	NCA	4.88	2.13	NCA	9.10	NCA
1990	4.55	2.44	4.88	2.13	5.26	9.10	6.67
2000	4.55	2.44	4.88	2.13	5.26	9.10	6.67

System Weight. Parameter values are based on a system capacity of 1 kWhr per charge/discharge cycle. Parameter values are presented in Table 69.

Table 69. BATTERY SYSTEM WEIGHT

PARAMETER: Weight

UNITS: Pounds/kWhr capacity

Year of Value	BATTERIES						
	Zn/Cl_2	Zn/Br_2	Ni/Fe	Li-Al/FeS_2	Na/S	Lead Acide	Redox Cr-Fe
1980	NCA	NCA	NCA	NCA	NCA	9.80E01	NCA
1985	NCA	NCA	5.62E01	2.60E01	NCA	7.36E01	NCA
1990	2.61E01	4.05E01	5.32E01	2.54E01	3.44E01	6.76E01	3.60E01
2000	2.44E01	4.05E01	4.89E01	2.36E01	2.83E01	6.28E01	3.60E01

Summary. The 1990 values for the above parameters are summarized in Table 70.

Fuel Requirements and Capabilities. Battery systems are fueled by electricity.

Charging Time. Battery systems have a "Charging Time" of 4 hours. They may be charged more rapidly, but usually with a penalty on efficiency and lifetime.

Discharge Time. Battery systems have a "Discharge Time" of 8 hours. Discharge times of as little as 4 hours are possible with little negative impact on efficiency on lifetime. Short discharge times negatively impact efficiency and lifetime.

Reliability. $LiAl/FeS_2$ and Na/S battery systems "Reliability" have an ordinal score of 3 indicating average reliability because of their high operating temperature. All other battery systems have a score of 4 indicating moderate reliability.

Environmental Constraints. With the exception of Zn/Cl_2 and Zn/Br_2 battery systems, battery systems have an ordinal score of 5 for "Environmental Constraints" indicating minimum potential environmental constraints. Zn/Cl_2 and Zn/Br_2 battery systems have a score of 4 indicating moderate potential environmental constraint because of potential for release of toxic chlorine (Cl_2) or bromine (Br_2) fumes.

Table 70. BATTERY SYSTEMS 1990 PARAMETER VALUES, 1 kWhr CAPACITY

Parameter	Zn/Cl_2	Zn/Br_2	Ni/Fe	$Li-Al/FeS_2$	Na/S	Lead-Acid	Redox Cr-Fe
Type	Mobile	Mobile	Mobile	Mobile	Mobile	Mobile	Mobile
System Acquisition Cost, $ (1980)	96.0	65.6	135	97.6	86.6	118	75.8
Annual Operation and Maintenance Cost, $ (1980)	1.92	1.31	2.70	1.95	1.73	2.36	1.52
Efficiency, %	79.4	71.8	65.0	75.0	82.5	82.0	75.0
Annual Electricity for Charging, kWhr	1020	1130	1250	1080	983	989	1080
Annual Cost of Electricity for Charging, $ (1980)							
0% Fuel Escalation	28.5	31.5	34.8	30.2	27.4	27.6	30.2
5% Fuel Escalation	46.5	51.4	56.8	49.2	44.7	45.0	49.2
10% Fuel Escalation	74.0	81.8	90.3	78.3	71.2	71.6	78.3
Life-Cycle Cost, $/kWhr stored (1980)							
0% Fuel Escalation	28.5	31.5	34.8	30.2	27.4	27.6	30.2
5% Fuel Escalation	46.5	51.4	56.8	49.2	44.7	45.0	49.2
10% Fuel Escalation	74.0	81.8	90.3	78.3	71.2	71.6	78.3
Life-Cycle Cost, $/kWhr stored (1980)							
0% Fuel Escalation	0.0425	0.0364	0.0598	0.0462	0.0449	0.0789	0.0259
5% Fuel Escalation	0.0664	0.0628	0.089	0.0715	0.0679	0.102	0.0511
10% Fuel Escalation	0.127	0.13	0.163	0.136	0.126	0.161	0.116
System Volume, ft^3	4.55	2.44	4.88	2.13	5.26	9.10	6.67
System Weight, lbs	26.1	40.5	53.2	25.4	34.4	67.6	36.0

Location Constraints. Battery systems have an ordinal score of 3 indicating average locational constraints. They must be located near a source of electricity. Toxic or explosive gases can be generated; therefore proper siting is important.

Operation Constraints. Battery systems have an ordinal score of 3 indicating average turn-down capability. They have no overload capability, except as designed.

Thermal Energy Storage Systems

There are six thermal storage materials considered in this study: Olivine Ceramic Brick, Magnesite Ceramic Brick, Calcium Chloride Hexahydrate, Sodium Sulfate Decahydrate, (Glauber's Salt), Sodium Thiosulfate Pentahydrate, and Form-Stable Polyethylene. The two brick materials are charged with electric resistance heating (Figure 47) and operate at temperatures around 1200°F. The latter four materials are phase-change materials and are charged with a working fluid (Figure 47). The operating temperatures are: Sodium Sulfate Decahydrate, about 73°F; Calcium Chloride Hexahydrate, about 81°F; Sodium Thiosulfate Pentahydrate, about 117°F; and Form-Stable Polyethylene, about 225°F. Although all of these media can be used for space heating, the Form-Stable Polyethylene is typically considered for use with absorption chillers.

Technology Status. All media are commercially available except for Sodium Thiosulfate Pentahydrate, which is expected to be commercial in 1985, and Form-Stable Polyethylene, which is expected to be commercial in 1990. The leading system using Sodium Thiosulfate Pentahydrate transfers heat to and from the salt with an immiscible liquid. A way must sill be developed to prevent emulsification of the liquids and consequent replacement of the medium. Commercialization of Form-Stable Polyethylene awaits successful scale-up of the pilot development unit and volume production (estimated to be greater than 10 million pounds per year) before it can be commercialized.

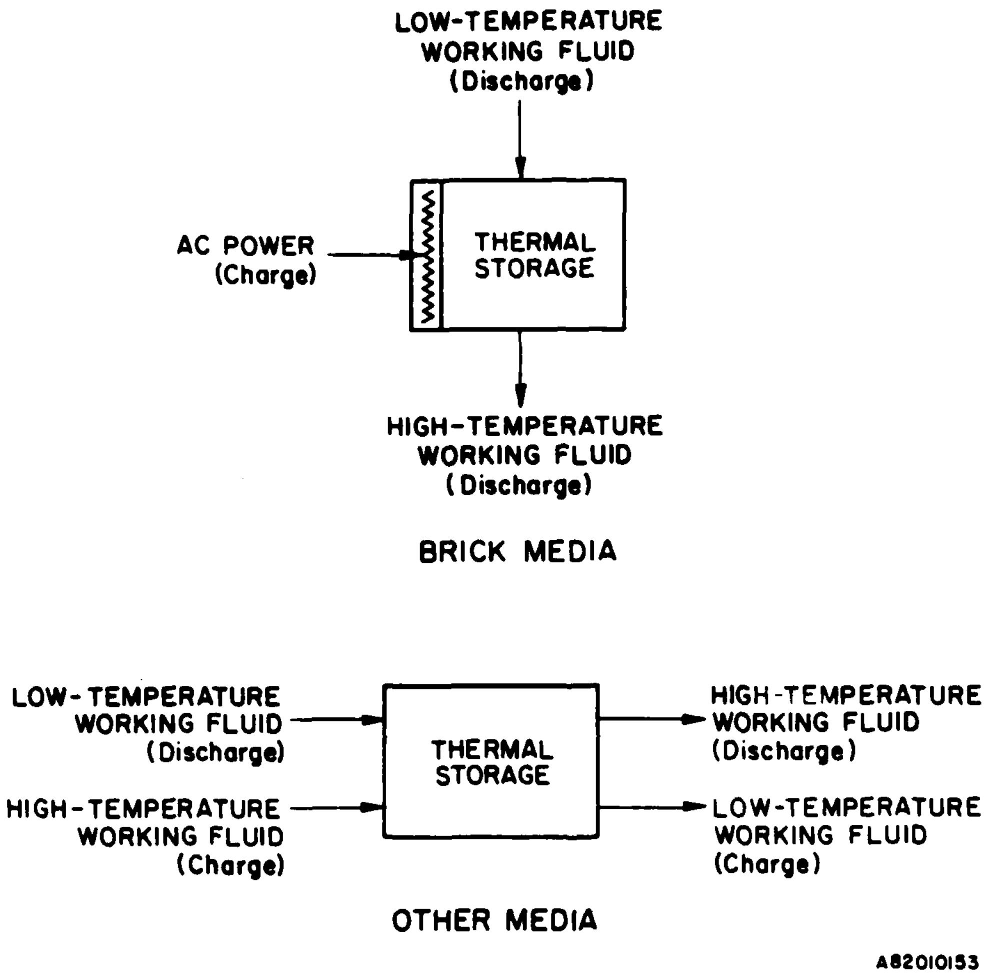

Figure 47. THERMAL ENERGY STORAGE SYSTEMS

Type. Thermal energy storage systems are mobile or fixed, as shown in Table 71.

Table 71. THERMAL ENERGY STORAGE SYSTEM TYPE

PARAMETER: TYPE UNITS: Mobile (M)/Transportable (T)/Fixed (F)

Thermal Energy Capacity, 10^3Btu	Year	$CaCl \cdot 6\ H_2O$	$Na_2SO_4 \cdot 10\ H_2O$	$NaS_2O_3 \cdot 5\ H_2O$	Olivine Ceramic	Magnisite Ceramic	Form-Stable Polyethylene
50	1980	M	M	NCA	M	M	NCA
	1985	M	M	M	M	M	NCA
	1990	M	M	M	M	M	M
	2000	M	M	M	M	M	M
100	1980	M	M	NCA	M	M	NCA
	1985	M	M	M	M	M	NCA
	1990	M	M	M	M	M	M
	2000	M	M	M	M	M	M
250	1980	M	M	NCA	M	M	NCA
	1985	M	M	M	M	M	NCA
	1990	M	M	M	M	M	M
	2000	M	M	M	M	M	M
500	1980	M	M	NCA	F	F	NCA
	1985	M	M	M	F	F	NCA
	1990	M	M	M	F	F	M
	2000	M	M	M	F	F	M
1000	1980	M	M	NCA	F	F	NCA
	1985	M	M	M	F	F	NCA
	1990	M	M	M	F	F	M
	2000	M	M	M	F	F	M
5000	1980	M	M	NCA	F	F	NCA
	1985	M	M	M	F	F	NCA
	1990	M	M	M	F	F	M
	2000	M	M	M	F	F	M
12500	1980	M	M	NCA	F	F	NCA
	1985	M	M	M	F	F	NCA
	1990	M	M	M	F	F	M
	2000	M	M	M	F	F	M
25,000	1980	M	M	NCA	F	F	NCA
	1985	M	M	M	F	F	NCA
	1990	M	M	M	F	F	M
	2000	M	M	M	F	F	M
37,500	1980	F	M	NCA	F	F	NCA
	1985	F	M	M	F	F	NCA
	1990	F	M	M	F	F	M
	2000	F	M	M	F	F	M
50,000	1980	F	M	NCA	F	F	NCA
	1985	F	M	M	F	F	NCA
	1990	F	M	M	F	F	F
	2000	F	M	M	F	F	F
250,000	1980	F	F	NCA	F	F	NCA
	1985	F	F	F	F	F	NCA
	1990	F	F	F	F	F	F
	2000	F	F	F	F	F	F

System Acquisition Cost. Acquisition costs are shown in Table 72. Costs for the year 1990 are shown in Figure 48 for comparison of the media.

Table 72. THERMAL ENERGY STORAGE SYSTEM ACQUISITION COST

PARAMETER: SYSTEM ACQUISITION COST UNITS: 1980 Dollars

Thermal Energy Capacity, 10^3Btu	Year	$CaCl \cdot 6H_2O$	$Na_2SO_4 \cdot 10H_2O$	$NaS_2O_3 \cdot 5H_2O$	Olivine Ceramic	Magnisite Ceramic	Form-Stable Polyethylene
50	1980	503	776	NCA	255	502	NCA
	1985	453	698	491	255	313	NCA
	1990	453	698	491	255	313	812
	2000	453	698	491	255	313	812
100	1980	867	1360	NCA	485	892	NCA
	1985	780	1220	842	485	558	NCA
	1990	780	1220	842	485	558	1400
	2000	780	1220	842	485	558	1400
250	1980	1740	2790	NCA	1130	1880	NCA
	1985	1570	2510	1680	1130	1180	NCA
	1990	1570	2510	1680	1130	1180	2780
	2000	1570	2510	1680	1130	1180	2780
500	1980	2870	4730	NCA	2140	3270	NCA
	1985	2580	4260	2750	2140	2040	NCA
	1990	2580	4260	2750	2140	2040	4460
	2000	2580	4260	2750	2140	2040	4460
1000	1980	4590	7830	NCA	4040	5600	NCA
	1985	4130	7050	4330	4040	3500	NCA
	1990	4130	7050	4330	4040	3500	6710
	2000	4130	7050	4330	4040	3500	6710
5000	1980	10600	21900	NCA	17400	18000	NCA
	1985	9540	19700	9300	17400	11300	NCA
	1990	9540	19700	9300	17400	11300	7950
	2000	9540	19700	9300	17400	11300	7950
12500	1980	26500	32000	NCA	43500	45000	NCA
	1985	23900	28800	23300	43500	28100	NCA
	1990	23900	28800	23300	43500	28100	19900
	2000	23900	28800	23300	43500	28100	19900
25,000	1980	53000	64000	NCA	87000	90000	NCA
	1985	47700	57600	46500	87000	56300	NCA
	1990	47700	57600	46500	87000	56300	39800
	2000	47700	57600	46500	87000	56300	39800
37,500	1980	79500	96000	NCA	131000	135000	NCA
	1985	71600	86400	69800	131000	84400	NCA
	1990	71600	86400	69800	131000	84400	59600
	2000	71600	86400	69800	131000	84400	59600
50,000	1980	106000	128000	NCA	174000	180000	NCA
	1985	95400	115000	93000	174000	113000	NCA
	1990	95400	115000	93000	174000	113000	79500
	2000	95400	115000	93000	174000	113000	79500
250,000	1980	530000	640000	NCA	870000	900000	NCA
	1985	477000	576000	465000	870000	563000	NCA
	1990	477000	576000	465000	870000	563000	398000
	2000	477000	576000	465000	870000	563000	398000

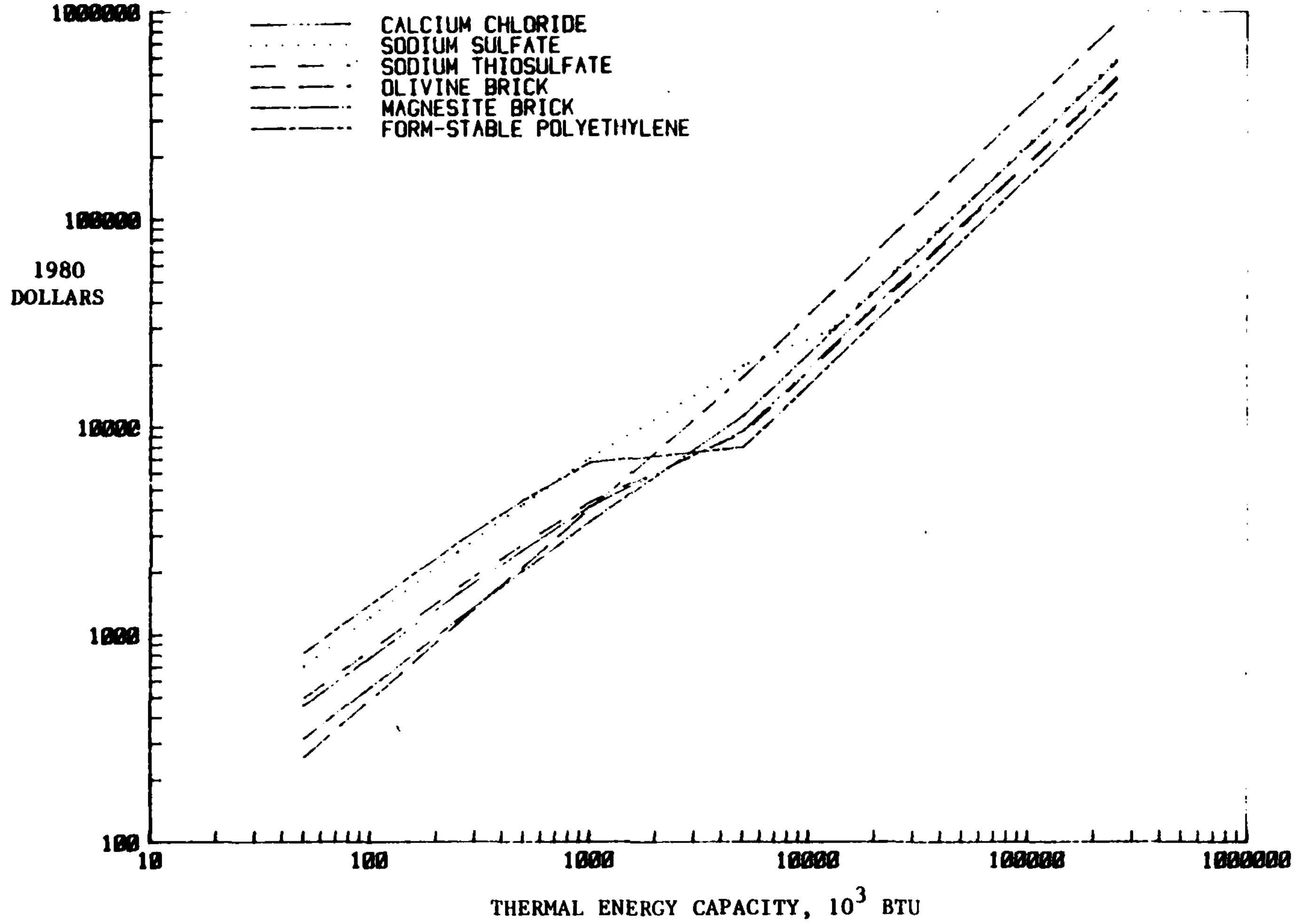

Figure 48. THERMAL ENERGY STORAGE ACQUISITION COSTS

Operation and Maintenance. Annual O&M costs are shown in Table 73. These costs are graphed for 1990 in Figure 49.

Table 73. THERMAL ENERGY STORAGE OPERATION AND MAINTENANCE COST

PARAMETER: ANNUAL O & M COSTS UNITS: 1980 Dollars

Thermal Energy Capacity, 10^3Btu	Year	$CaCl \cdot 6\ H_2O$	$Na_2SO_4 \cdot 10\ H_2O$	$NaS_2O_3 \cdot 5\ H_2O$	Olivine Ceramic	Magnisite Ceramic	Form-Stable Polyethylene
50	1980	2.63	41.10	NCA	7.88	15.50	NCA
	1985	2.37	37.00	63.80	7.88	9.69	NCA
	1990	2.37	37.00	63.80	7.88	9.69	24.40
	2000	2.37	37.00	63.80	7.88	9.69	24.40
100	1980	4.98	72.10	NCA	13.10	24.20	NCA
	1985	4.48	64.90	109.00	13.10	15.10	NCA
	1990	4.48	64.90	109.00	13.10	15.10	42.00
	2000	4.48	64.90	109.00	13.10	15.15	42.00
250	1980	11.60	148.00	NCA	24.90	41.40	NCA
	1985	10.40	133.00	218.00	24.90	25.90	NCA
	1990	10.40	133.00	218.00	24.90	25.90	83.40
	2000	10.40	133.00	218.00	24.90	25.90	83.40
500	1980	21.70	251.00	NCA	38.90	59.50	NCA
	1985	19.50	226.00	358.00	38.90	37.20	NCA
	1990	19.50	226.00	358.00	38.90	37.20	134.00
	2000	19.50	226.00	358.00	38.90	37.20	134.00
1000	1980	40.60	415.00	NCA	58.20	80.60	NCA
	1985	36.50	374.00	563.00	58.20	50.40	NCA
	1990	36.50	374.00	563.00	58.20	50.40	201.00
	2000	36.50	374.00	563.00	58.20	50.40	201.00
5000	1980	171.00	1160.00	NCA	97.40	101.00	NCA
	1985	154.00	1040.00	1210.00	97.40	63.10	NCA
	1990	154.00	1040.00	1210.00	97.40	63.10	239.00
	2000	154.00	1040.00	1210.00	97.40	63.10	239.00
12500	1980	380.00	1700.00	NCA	244.00	252.00	NCA
	1985	342.00	1530.00	3030.00	244.00	158.00	NCA
	1990	342.00	1530.00	3030.00	244.00	158.00	597.00
	2000	342.00	1530.00	3030.00	244.00	158.00	597.00
25,000	1980	691	3390	NCA	487	504	NCA
	1985	622	3050	6050	487	315	NCA
	1990	622	3050	6050	487	315	1190
	2000	622	3050	6050	487	315	1190
37,500	1980	976	5090	NCA	734	756	NCA
	1985	878	4580	9070	734	473	NCA
	1990	878	4580	9070	734	473	1790
	2000	878	4580	9070	734	473	1790
50,000	1980	1240	6780	NCA	974	1010	NCA
	1985	1120	6100	12100	974	631	NCA
	1990	1120	6100	12100	974	631	2390
	2000	1120	6100	12100	974	631	2390
250,000	1980	4610	33900	NCA	4870	5040	NCA
	1985	4150	30500	60500	4870	3150	NCA
	1990	4150	3050[illegible]	60500	4870	3150	11900
	2000	4150	30500	60500	4870	3150	11900

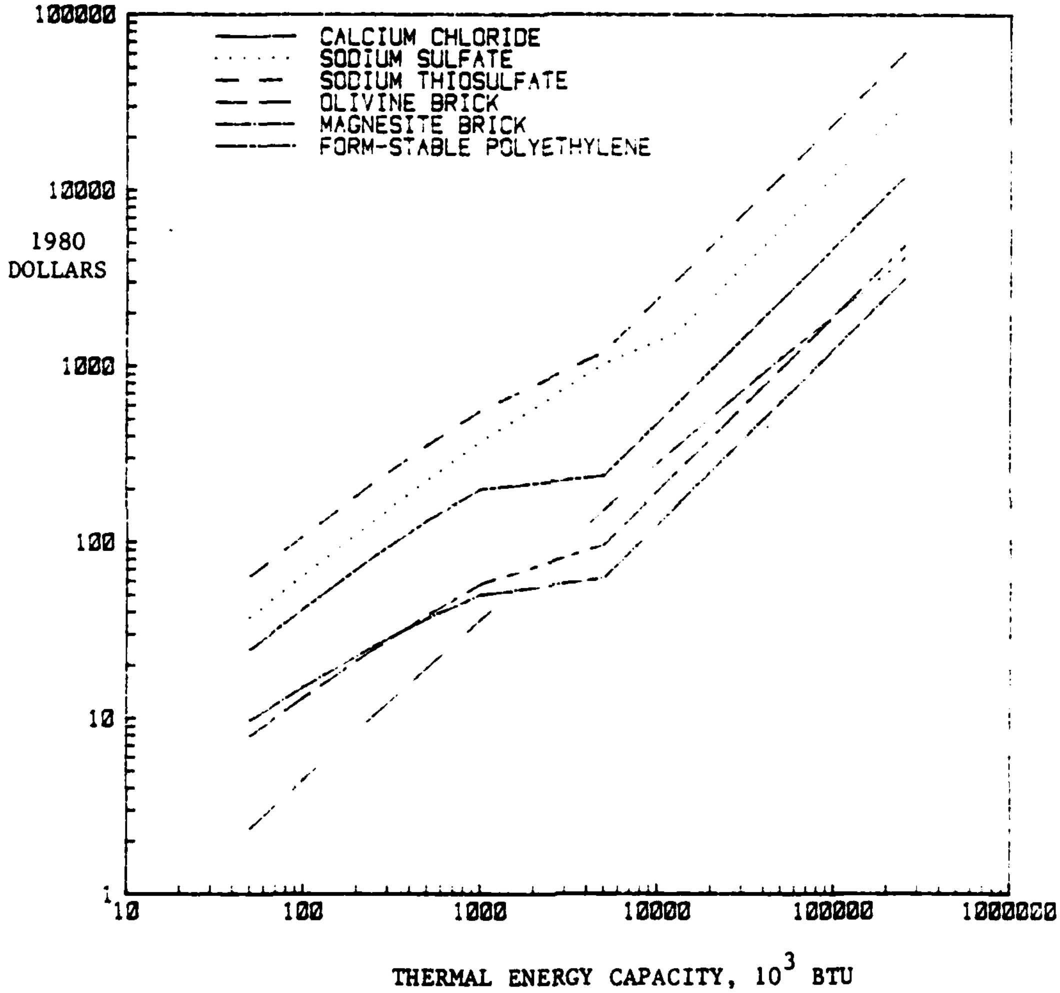

Figure 49. THERMAL ENERGY STORAGE O&M COSTS

System Efficiency. All TES systems are presumed to have 95% efficiencies. This is the thermal energy output divided by the fuel required for charging.

Annual Energy Required for Charging. The annual energy required for charging the systems are shown by thermal energy capacity in Table 74. This requirement is shown graphically in Figure 50.

Table 74. ANNUAL ENERGY REQUIRED FOR CHARGING THERMAL ENERGY STORAGE SYSTEMS

PARAMETER: ANNUAL ENERGY REQUIRED FOR CHARGING UNITS: Btu

Thermal Energy Capacity, 10^3Btu	Year	$CaCl \cdot 6\ H_2O$	$Na_2SO_4 \cdot 10\ H_2O$	$NaS_2O_3 \cdot 5\ H_2O$	Olivine Ceramic	Magnisite Ceramic	Form-Stable Polyethylene
50	1980	1.92E07	1.92E07	NCA	1.92E07	1.92E07	NCA
	1985	1.92E07	1.92E07	1.92E07	1.92E07	1.92E07	NCA
	1990	1.92E07	1.92E07	1.92E07	1.92E07	1.92E07	1.92E07
	2000	1.92E07	1.92E07	1.92E07	1.92E07	1.92E07	1.92E07
100	1980	3.84E07	3.84E07	NCA	3.84E07	3.84E07	NCA
	1985	3.84E07	3.84E07	3.84E07	3.84E07	3.84E07	NCA
	1990	3.84E07	3.84E07	3.84E07	3.84E07	3.84E07	3.84E07
	2000	3.84E07	3.84E07	3.84E07	3.84E07	3.84E07	3.84E07
250	1980	9.61E07	9.61E07	NCA	9.61E07	9.61E07	NCA
	1985	9.61E07	9.61E07	9.61E07	9.61E07	9.61E07	NCA
	1990	9.61E07	9.61E07	9.61E07	9.61E07	9.61E07	9.61E07
	2000	9.61E07	9.61E07	9.61E07	9.61E07	9.61E07	9.61E07
500	1980	1.92E08	1.92E08	NCA	1.92E08	1.92E08	NCA
	1985	1.92E08	1.92E08	1.92E08	1.92E08	1.92E08	NCA
	1990	1.92E08	1.92E08	1.92E08	1.92E08	1.92E08	1.92E08
	2000	1.92E08	1.92E08	1.92E08	1.92E08	1.92E08	1.92E08
1000	1980	3.84E08	3.84E08	NCA	3.84E08	3.84E08	NCA
	1985	3.84E08	3.84E08	3.84E08	3.84E08	3.84E08	NCA
	1990	3.84E08	3.84E08	3.84E08	3.84E08	3.84E08	3.84E08
	2000	3.84E08	3.84E08	3.84E08	3.84E08	3.84E08	3.84E08
5000	1980	1.92E09	1.92E09	NCA	1.92E09	1.92E09	NCA
	1985	1.92E09	1.92E09	1.92E09	1.92E09	1.92E09	NCA
	1990	1.92E09	1.92E09	1.92E09	1.92E09	1.92E09	1.92E09
	2000	1.92E08	1.92E09	1.92E09	1.92E09	1.92E09	1.92E09
12500	1980	4.80E09	4.80E09	NCA	4.80E09	4.80E09	NCA
	1985	4.80E09	4.80E09	4.80E09	4.80E09	4.80E09	NCA
	1990	4.80E09	4.80E09	4.80E09	4.80E09	4.80E09	4.80E09
	2000	4.80E09	4.80E09	4.80E09	4.80E09	4.80E09	4.80E09
25,000	1980	9.61E09	9.61E09	NCA	9.61E09	9.61E09	NCA
	1985	9.61E09	9.61E09	9.61E09	9.61E09	9.61E09	NCA
	1990	9.61E09	9.61E09	9.61E09	9.61E09	9.61E09	9.61E09
	2000	9.61E09	9.61E09	9.61E09	9.61E09	9.61E09	9.61E09
37,500	1980	1.44E10	1.44E10	NCA	1.44E10	1.44E10	NCA
	1985	1.44E10	1.44E10	1.44E10	1.44E10	1.44E10	NCA
	1990	1.44E10	1.44E10	1.44E10	1.44E10	1.44E10	1.44E10
	2000	1.44E10	1.44E10	1.44E10	1.44E10	1.44E10	1.44E10
50,000	1980	1.92E10	1.92E10	NCA	1.92E10	1.92E10	NCA
	1985	1.92E10	1.92E10	1.92E10	1.92E10	1.92E10	NCA
	1990	1.92E10	1.92E10	1.92E10	1.92E10	1.92E10	1.92E10
	2000	1.92E10	1.92E10	1.92E10	1.92E10	1.92E10	1.92E10
250,000	1980	9.61E10	9.61E10	NCA	9.61E10	9.61E10	NCA
	1985	9.61E10	9.61E10	9.61E10	9.61E10	9.61E10	NCA
	1990	9.61E10	9.61E10	9.61E10	9.61E10	9.61E10	9.61E10
	2000	9.61E10	9.61E10	9.61E10	9.61E10	9.61E10	9.61E10

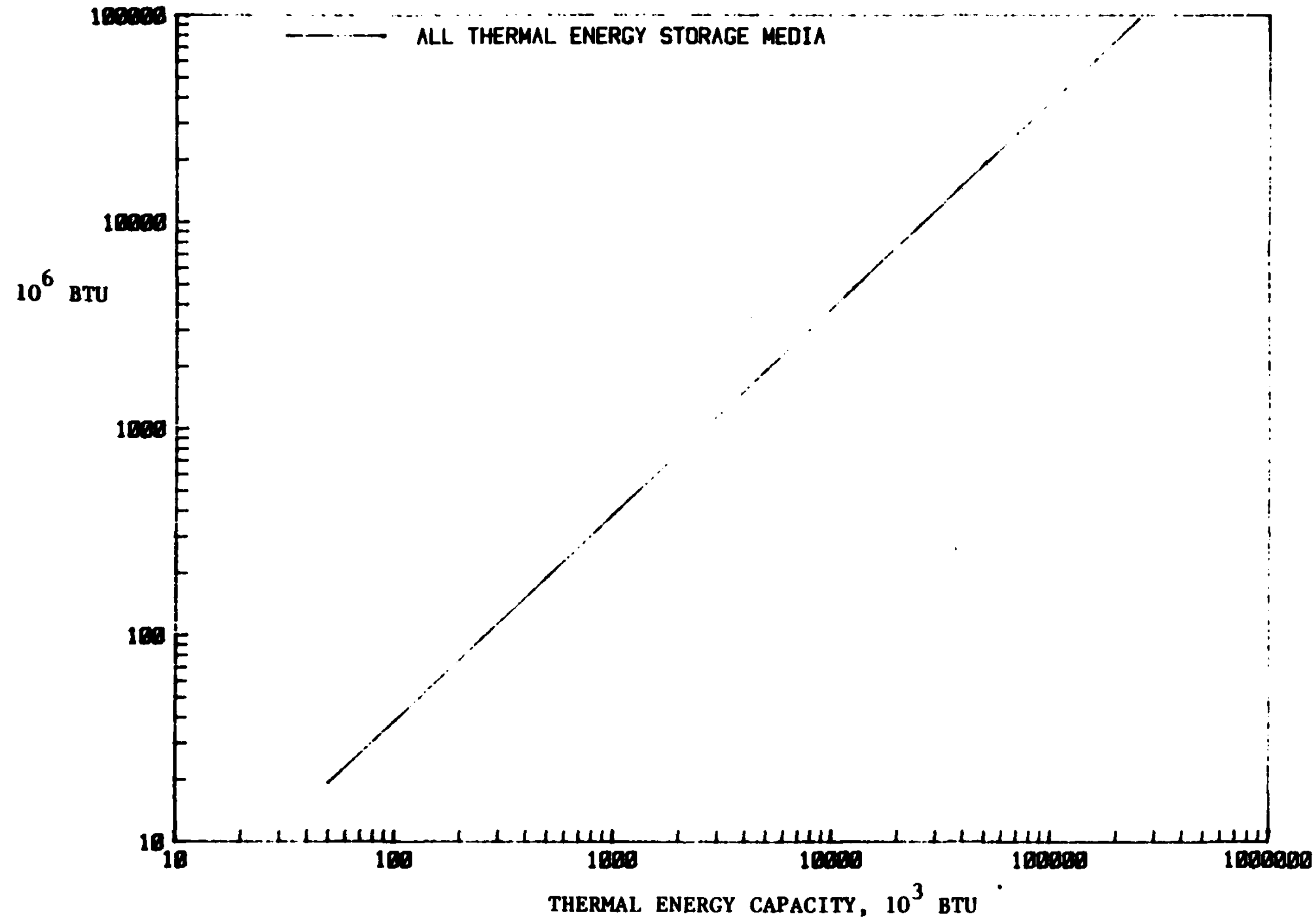

Figure 50. THERMAL ENERGY STORAGE ANNUAL ENERGY REQUIRED FOR CHARGING

Annual Fuel Cost. Fuel costs are presented in Table 75. These values reflect constant 1980 dollars, and are not escalated to account for future price increases.

Table 75. ANNUAL COST OF ENERGY FOR CHARGING THERMAL ENERGY STORAGE SYSTEMS

PARAMETER: ANNUAL COST OF ENERGY REQUIRED FOR CHARGING UNITS: 1980 Dollars

Thermal Energy Capacity, 10^3Btu	Year	$CaCl \cdot 6 H_2O$	$Na_2SO_4 \cdot 10 H_2O$	$NaS_2O_3 \cdot 5 H_2O$	Olivine Ceramic	Magnisite Ceramic	Form-Stable Polyethylene
50	1980	0	0	NCA	89	89	NCA
	1985	0	0	0	157	157	NCA
	1990	0	0	0	157	157	0
	2000	0	0	0	157	157	0
100	1980	0	0	NCA	178	178	NCA
	1985	0	0	0	314	314	NCA
	1990	0	0	0	314	314	0
	2000	0	0	0	314	314	0
250	1980	0	0	NCA	446	446	NCA
	1985	0	0	0	786	786	NCA
	1990	0	0	0	786	786	0
	2000	0	0	0	786	786	0
500	1980	0	0	NCA	891	891	NCA
	1985	0	0	0	1570	1570	NCA
	1990	0	0	0	1570	1570	0
	2000	0	0	0	1570	1570	0
1000	1980	0	0	NCA	1780	1780	NCA
	1985	0	0	0	3140	3140	NCA
	1990	0	0	0	3140	3140	0
	2000	0	0	0	3140	3140	0
5000	1980	0	0	NCA	8910	8910	NCA
	1985	0	0	0	15700	15700	NCA
	1990	0	0	0	15700	15700	0
	2000	0	0	0	15700	15700	0
12500	1980	0	0	NCA	22300	22300	NCA
	1985	0	0	0	39300	39300	NCA
	1990	0	0	0	39300	39300	0
	2000	0	0	0	39300	39300	0
25,000	1980	0	0	NCA	44600	44600	NCA
	1985	0	0	0	78600	78600	NCA
	1990	0	0	0	78600	78600	0
	2000	0	0	0	78600	78600	0
37,500	1980	0	0	NCA	66800	66800	NCA
	1985	0	0	0	118000	118000	NCA
	1990	0	0	0	118000	118000	0
	2000	0	0	0	118000	118000	0
50,000	1980	0	0	NCA	89100	89100	NCA
	1985	0	0	0	157000	157000	NCA
	1990	0	0	0	157000	157000	0
	2000	0	0	0	157000	157000	0
250,000	1980	0	0	NCA	446000	446000	NCA
	1985	0	0	0	786000	786000	NCA
	1990	0	0	0	786000	786000	0
	2000	0	0	0	786000	786000	0

Life-Cycle Cost. Life-cycle costs are shown in Table 76 and Figure 51.

Table 76. THERMAL ENERGY STORAGE LIFE CYCLE COST

PARAMETER: LIFE-CYCLE COST UNITS: 1980 Dollars/10^6 Btu

Thermal Energy Capacity, 10^3Btu	Year	$CaCl \cdot 6\ H_2O$	$Na_2SO_4 \cdot 10\ H_2O$	$NaS_2O_3 \cdot 5\ H_2O$	Olivine Ceramic	Magnisite Ceramic	Form-Stable Polyethylene
50	1980	1.37	2.93	NCA	2.81	3.63	NCA
	1985	1.23	2.63	2.69	4.32	4.51	NCA
	1990	1.23	2.63	2.69	4.32	4.51	2.66
	2000	1.23	2.63	2.69	4.32	4.51	2.66
100	1980	1.18	2.57	NCA	2.75	3.40	NCA
	1985	1.07	2.31	2.30	4.25	4.37	NCA
	1990	1.07	2.31	2.30	4.25	4.37	2.29
	2000	1.07	2.31	2.30	4.25	4.37	2.29
250	1980	0.96	2.11	NCA	2.67	3.14	NCA
	1985	0.86	1.90	1.84	4.18	4.21	NCA
	1990	0.86	1.90	1.84	4.18	4.21	1.82
	2000	0.86	1.90	1.84	4.18	4.21	1.82
500	1980	0.80	1.79	NCA	2.62	2.96	NCA
	1985	0.72	1.61	1.51	4.12	4.09	NCA
	1990	0.72	1.61	1.51	4.12	4.09	1.46
	2000	0.72	1.61	1.51	4.12	4.09	1.46
1000	1980	0.64	1.48	NCA	2.56	2.79	NCA
	1985	0.58	1.33	1.19	4.07	3.99	NCA
	1990	0.58	1.33	1.19	4.07	3.99	1.10
	2000	0.58	1.33	1.19	4.07	3.99	1.10
5000	1980	0.31	0.83	NCA	2.45	2.47	NCA
	1985	0.28	0.74	0.51	3.96	3.79	NCA
	1990	0.28	0.74	0.51	3.96	3.79	0.26
	2000	0.28	0.74	0.51	3.96	3.79	0.26
12500	1980	0.31	0.48	NCA	2.45	2.47	NCA
	1985	0.28	0.44	0.51	3.96	3.79	NCA
	1990	0.28	0.44	0.51	3.96	3.79	0.26
	2000	0.28	0.44	0.51	3.96	3.79	0.26
25,000	1980	0.31	0.48	NCA	2.45	2.47	NCA
	1985	0.28	0.43	0.51	3.96	3.79	NCA
	1990	0.28	0.43	0.51	3.96	3.79	0.26
	2000	0.28	0.43	0.51	3.96	3.79	0.26
37,500	1980	0.30	0.48	NCA	2.45	2.47	NCA
	1985	0.27	0.43	0.51	3.96	3.79	NCA
	1990	0.27	0.43	0.51	3.96	3.79	0.26
	2000	0.27	0.43	0.51	3.96	3.79	0.26
50,000	1980	0.30	0.48	NCA	2.45	2.47	NCA
	1985	0.27	0.43	0.51	3.96	3.79	NCA
	1990	0.27	0.43	0.51	3.96	3.79	0.26
	2000	0.27	0.43	0.51	3.96	3.79	0.26
250,000	1980	0.30	0.48	NCA	2.45	2.47	NCA
	1985	0.27	0.43	0.51	3.96	3.79	NCA
	1990	0.27	0.43	0.51	3.96	3.79	0.26
	2000	0.27	0.43	0.51	3.96	3.79	0.26

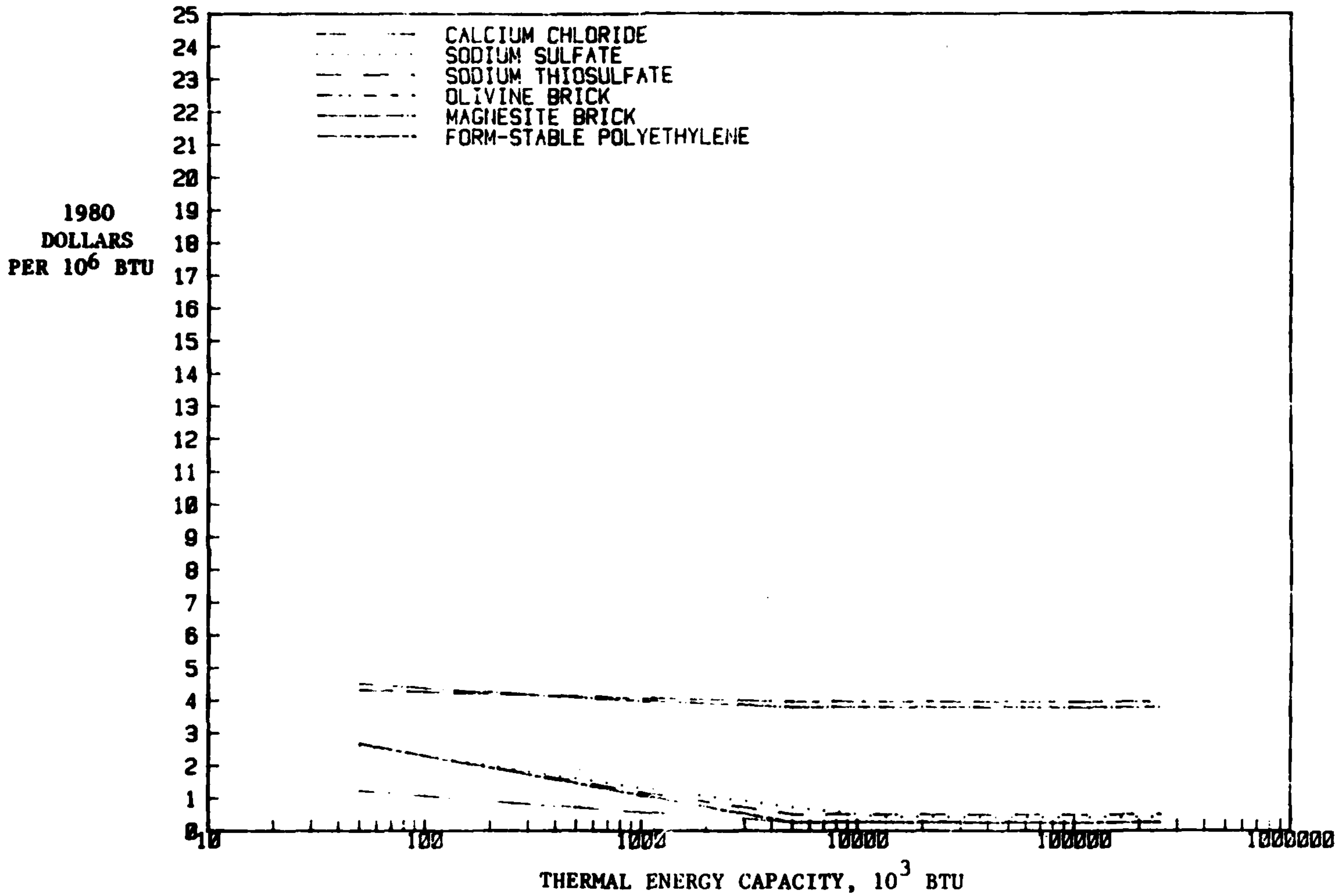

Figure 51. THERMAL ENERGY STORAGE LIFE CYCLE COST

Volume. System volumes are presented in Table 77.

Table 77. THERMAL ENERGY STORAGE SYSTEM VOLUME

PARAMETER: VOLUME UNITS: Cubic Feet

Thermal Energy Capacity, 10^3Btu	Year	$CaCl \cdot 6\ H_2O$	$Na_2SO_4 \cdot 10\ H_2O$	$NaS_2O_3 \cdot 5\ H_2O$	Olivine Ceramic	Magnisite Ceramic	Form-Stable Polyethylene
50	1980	12	14	NCA	8	5	NCA
	1985	12	14	7	8	5	NCA
	1990	12	14	7	8	5	10
	2000	12	14	7	8	5	10
100	1980	24	26	NCA	16	10	NCA
	1985	24	26	13	16	10	NCA
	1990	24	26	13	16	10	20
	2000	24	26	13	16	10	20
250	1980	59	60	NCA	40	22.5	NCA
	1985	59	60	33	40	22.5	NCA
	1990	59	60	33	40	22.5	50
	2000	59	60	33	40	22.5	50
500	1980	120	110	NCA	80	45	NCA
	1985	120	110	65	80	45	NCA
	1990	120	110	65	80	45	99
	2000	120	110	65	80	45	99
1000	1980	230	210	NCA	160	90	NCA
	1985	230	210	130	160	90	NCA
	1990	230	210	130	160	90	200
	2000	230	210	130	160	90	200
5000	1980	1200	920	NCA	800	400	NCA
	1985	1200	920	650	800	400	NCA
	1990	1200	920	650	800	400	990
	2000	1200	920	650	800	400	990
12500	1980	2900	2100	NCA	2000	860	NCA
	1985	2900	2100	1600	2000	860	NCA
	1990	2900	2100	1600	2000	860	2500
	2000	2900	2100	1600	2000	860	2500
25,000	1980	5700	4000	NCA	4000	1650	NCA
	1985	5700	4000	3300	4000	1650	NCA
	1990	5700	4000	3300	4000	1650	5000
	2000	5700	4000	3300	4000	1650	5000
37,500	1980	8500	5700	NCA	6000	2400	NCA
	1985	8500	5700	4900	6000	2400	NCA
	1990	8500	5700	4900	6000	2400	7400
	2000	8500	5700	4900	6000	2400	7400
50,000	1980	11000	7400	NCA	8000	3200	NCA
	1985	11000	7400	6500	8000	3200	NCA
	1990	11000	7400	6500	8000	3200	9900
	2000	11000	7400	6500	8000	3200	9900
250,000	1980	56000	31000	NCA	40000	14000	NCA
	1985	56000	31000	33000	40000	14000	NCA
	1990	56000	31000	33000	40000	14000	50000
	2000	56000	31000	33000	40000	14000	50000

Weight. Weights of the various systems are shown in Table 78.

Summary. The 1990 values of the above parameters are summarized in Table 79.

Table 78. THERMAL ENERGY STORAGE SYSTEM WEIGHT

PARAMETER: WEIGHT UNITS: POUNDS

Thermal Energy Capacity, 10^3Btu	Year	$CaCl\cdot 6\ H_2O$	$Na_2\ SO_4\ \cdot 10\ H_2O$	$NaS_2O_3\cdot 5\ H_2O$	Olivine Ceramic	Magnisite Ceramic	Form-Stable Polyethylene
50	1980	870	840	NCA	230	280	NCA
	1985	870	840	580	230	280	NCA
	1990	870	840	580	230	280	610
	2000	870	840	580	230	280	610
100	1980	1600	1600	NCA	450	560	NCA
	1985	1600	1600	1200	450	560	NCA
	1990	1600	1600	1200	450	560	1200
	2000	1600	1600	1200	450	560	1200
250	1980	3400	3600	NCA	1100	1400	NCA
	1985	3400	3600	2900	1100	1400	NCA
	1990	3400	3600	2900	1100	1400	3000
	2000	3400	3600	2900	1100	1400	3000
500	1980	6100	6700	NCA	2300	2700	NCA
	1985	6100	6700	5800	2300	2700	NCA
	1990	6100	6700	5800	2300	2700	6100
	2000	6100	6700	5800	2300	2700	6100
1000	1980	11000	12000	NCA	4500	5400	NCA
	1985	11000	12000	12000	4500	5400	NCA
	1990	11000	12000	12000	4500	5400	12000
	2000	11000	12000	12000	4500	5400	12000
5000	1980	39000	52000	NCA	23000	27000	NCA
	1985	39000	52000	58000	23000	27000	NCA
	1990	39000	52000	58000	23000	27000	61000
	2000	39000	52000	58000	23000	27000	61000
12500	1980	77000	120000	NCA	57000	67000	NCA
	1985	77000	120000	140000	57000	67000	NCA
	1990	77000	120000	140000	57000	67000	150000
	2000	77000	120000	140000	57000	67000	150000
25,000	1980	130000	130000	NCA	110000	130000	NCA
	1985	130000	130000	290000	110000	130000	NCA
	1990	130000	130000	290000	110000	130000	300000
	2000	130000	130000	290000	110000	130000	300000
37,500	1980	160000	300000	NCA	170000	190000	NCA
	1985	160000	300000	430000	170000	190000	NCA
	1990	160000	300000	430000	170000	190000	450000
	2000	160000	300000	430000	170000	190000	450000
50,000	1980	200000	390000	NCA	230000	260000	NCA
	1985	200000	390000	580000	230000	260000	NCA
	1990	200000	390000	580000	230000	260000	610000
	2000	200000	390000	580000	230000	260000	610000
250,000	1980	400000	1600000	NCA	1100000	1200000	NCA
	1985	400000	1600000	2900000	1100000	1200000	NCA
	1990	400000	1600000	2900000	1100000	1200000	3000000
	2000	400000	1600000	2900000	1100000	1200000	3000000

Table 79. THERMAL ENERGY STORAGE 1990 PARAMETER VALUES, 1 MILLION Btu CAPACITY

Parameter	Calcium Chloride	Sodium Sulfate	Sodium Thiosulfate	Olivine Ceramic	Magnesite Ceramic	Form-Stable Polyethylene
Type	Mobile	Mobile	Mobile	Fixed	Fixed	Mobile
System Acquisition Cost, $ (1980)	4130	7050	4330	4040	3500	6710
Annual Operations and Maintenance Cost, $ (1980)	36.50	374	563	58.20	50.40	201
Annual Energy Required for Charging, Btu	3.84E08	3.84E08	3.84E08	3.84E08	3.84E08	3.84E08
Annual Cost of Energy Required for Charging, $ (1980)	0	0	0	3140	3140	0
Life-Cycle Cost, $ (1980)/10^6 Btu						
0% Fuel Escalation	0.58	1.33	1.19	4.07	3.99	1.10
5% Fuel Escalation	3.69	4.46	4.30	9.05	8.97	4.21
10% Fuel Escalation	8.34	9.09	8.95	21.79	21.89	8.86
System Volume, ft^3	230	210	130	160	90	200
System Weight, lbs	11,000	12,000	12,000	4500	5400	12,000

Fuel Requirements and Capabilities. Salt phase-change media can use solar energy or waste heat at temperatures up to about 150°F. Olivine and ceramic brick systems require electricity as fuel for charging. The bricks could be used in systems designed for direct high-temperature heat storage. Form-stable polyethylene requires heat at a temperature of about 225°F.

Charge and Discharge Times. The time required to charge calcium chloride systems is typically 9 hours, for sodium sulfate 7 hours, for sodium thiosulfate 7 hours, for olivine brick 8 hours, for magnesite brick 8 hours, and for form-stable polyethylene 13 hours. The time required to discharge calcium chloride systems is typically 15 hours, for sodium sulfate 7 hours, for sodium thiosulfate 7 hours, for olivine brick 10 hours, for magnesite brick 14 hours, and for form-stable polyethylene 6 hours.

Operation and Maintenance. Calcium chloride systems are very simple to operate and maintain. They have no moving parts unless a fan is used to increase the rate of heat transfer. The plastic tubes holding the salt should not be subjected to temperatures above 150°F. The tubes should be inspected for breaks, as lifetime is decreased when moisture enters or leaves the salt. Additionally, the salt is corrosive, although it is compatible with polyethylene, various plastic films, and drawn and seamed steel.

Some systems uitlizing sodium sulfate and sodium thiosulfate require pumps or agitation for mixing the hydrate, which adds to their O&M requirements. These salts are also corrosive.

The olivine and magnesite systems can operate automatically based on outside air temperature, time-of-day, or a signal from the electric utility; they can also be turned on manually. Moving parts in the system include a fan and damper mechanism to control air flow.

The form-stable polyethylene system is required to operate at 225°F. Its operation will probably be automatically integrated with an absorption air-conditioning system.

Reliability. Systems utilizing olivine brick, magnesite brick, calcium chloride, sodium sulfate and form-stable polyethylene have moderate reliability (ordinal score of 4). Sodium thiosulfate systems have average reliability (ordinal score of 3); this lower reliability is expected because of more moving parts.

Environmental Constraints. All systems are expected to have minimum potential environmental constraints (ordinal score of 5). There is a potential for a minor noise problem when fans or pumps are used. There is also a potential for chemical leaks in the salt-based systems; the salts are roughly as toxic as table salt.

Locational Constraints. All thermal enrgy storage systems have moderate locational constraints (ordinal score of 4). For the salt-based systems electricity may be required for fan or pump operation or charging, depending on the application. Some systems rely on passive solar gain, in which case adequate solar insolation must be available at the site.

The olivine and magnesite brick systems require electricity service of 208 volt AC (minimum). Time-of-day electric rates are required for cost savings.

Operational Constraints. Systems using olivine brick, magnesite brick, calcium chloride, sodium sulfate and form-stable polyethylene have average turndown capability (ordinal score of 3). Systems based on sodium thiosulfate have moderate turndown capability with a moderate efficiency penalty (ordinal score of 4).

CONCLUSIONS

The data presented in this report were provided to indicate the relative attributes of each of the technologies. The data were gathered during 1981-1982. Obviously, with developing technologies, the expected performance of the technology changes over time as more is learned about the technology and its performance. The key in technology development for competitive systems is for the developers to change the performance of their technology relative to competition. Consequently, the data provided here represent the technologies and the expectations of development during 1981-1982. As the technologies are developed over time, not only will the absolute values of performance change but so will future expectations of performance improvements and so will the relative performance of the technologies.

Because of this, the data presented here can only represent a starting point from which the technologies must be continuously monitored to insure that significant changes in the relative performance of the various technologies are incorporated into the data base.

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